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This volume contains the Annual Report of the Director for the year 1954 and contributions from the WOODS HOLE OCEANOGRAPHIC INSTITUTION which appeared in 1954 except for those published in *Papers in Physical Oceanography and Meteorology*

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RELATION BETWEEN CIRCULATION AND PLANKTONIC POPULATIONS IN ESTUARIES[1]

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INTRODUCTION

The study of planktonic populations in estuaries is complicated by the continuous movement of the water. The tides move the water back and forth, so that at a given location the population at low tide may be quite different from that present at high tide. In addition to the obvious flood and ebb tidal movements, the water masses have a net motion which results from inequalities of the tidal movements. The seaward drift of the diluted water must be adequate to remove the fresh water constantly added to the estuary from the rivers.

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[1] Contribution No. 598 from the Woods Hole Oceanographic Institution.

The landward drift of more saline water must supply enough sea water to maintain the salt balance by bringing into the estuary an amount of salt equal to that entrained with the fresh water. It is obvious that planktonic populations will be distributed throughout the estuary by these water movements.

If the circulation were the only process influencing the size of the population throughout the estuary, the problem would be very simple. For a population originating in the seaward end of the estuary the expected distribution would be directly proportional to the salt content of any water sample. If the population originated at the fresh water end of the estuary its distribution would be proportional to that of the fresh water, *i.e.* inversely proportional to the salt content. These simple relationships are never found because the population grows or dies within the estuary, and frequently the reproduction rate or the death rate is very different in different parts of the estuary.

The rates of reproduction or of death of a planktonic population within the estuary can be derived only when the rate of circulation is taken into account. It is the purpose of this paper to indicate how this may be done, and to illustrate how the circulation may impose minimum requirements for the rate of reproduction of a population if it is to survive within the estuary.

THEORETICAL CONSIDERATIONS

A basic assumption in the analysis is that the populations considered are distributed at random by the same processes that control the distribution of fresh and salt waters. The distribution of populations which exhibit vertical gradients, by means of vertical migrations for example, may be unpredictable by these methods. High concentrations of the population in the surface, fresher water would result in more rapid dispersion than the average, since this is the route by which the fresh water escapes seaward. High concentrations in the deeper, more saline water, which is the location of the landward counterdrift, would result in a slower dispersion than the average. Since vertical distribution may vary with time, and vertical migrations may be diurnal in character, and thus out of phase with the flood and ebb of the tide, generalizations concerning the distribution of such populations are not attempted in this paper.

The net result of the circulation in each estuary must be to move seaward, across any complete cross section, during each tidal cycle, a volume of fresh water equal to that introduced by the river during the same period of time. It has been shown that, for selected segments of an estuary, an exchange ratio can be defined as the proportion of the water which moves seaward and does not return on a following flood tide. This same proportion of any planktonic population must also be lost downstream. There is, thus, a constant drain on the population, and enough new individuals to balance this drain must be produced if the population is to maintain itself.

Let us first consider the case of an endemic population, by which is meant specifically a population which is maintaining itself within the estuary and is not receiving recruits from upstream or downstream during the tidal cycle. For such a population the standard growth equation and a simplified circulation equation can be combined. The growth equation is:

$$P_t = P_0 e^{kt} \qquad (1)$$

in which P_0 and P_t are the size of the population initially and after time t, and k is the coefficient of reproduction rate.

As a result of the circulation alone, the population remaining after being depleted by a series of tidal cycles is given by:

$$P_m = P_0 (1 - r)^m \qquad (2)$$

in which m is the number of tidal cycles, and r is the exchange ratio, defined as the proportion of the water moving seaward during each tidal cycle, which does not return on the following flood tide (Ketchum 1951).

Expressing time in the growth equation in terms of tidal cycles, the combination then gives:

$$P_m = P_0 (1 - r)^m e^{mk} \qquad (3)$$

If the population remains constant, $P_m = P_0$, and the growth rate required to balance the depletion by circulation can be defined in terms of the exchange ratio, *i.e.*

$$e^{mk} = \frac{1}{(1 - r)^m} \qquad (4)$$

or

$$k = - \ln (1 - r) \qquad (5)$$

This equation thus defines the rate of reproduction necessary to maintain a population in the estuary in spite of continuous depletion by the circulation. Obviously, if the rate of reproduction is greater than this value the population will increase; if less, the population will decrease.

The relative size of a population in a tidal segment of an estuary as a result of various growth rates is given in Figure 1. For this example an exchange ratio of 0.5 has been used. A similar pattern would be obtained for any other exchange ratio, except that the time scale would be changed. The numbers on the chart indicate the size which would be attained by the population if the circulation were not constantly depleting it. If the population did not reproduce at all it would de-

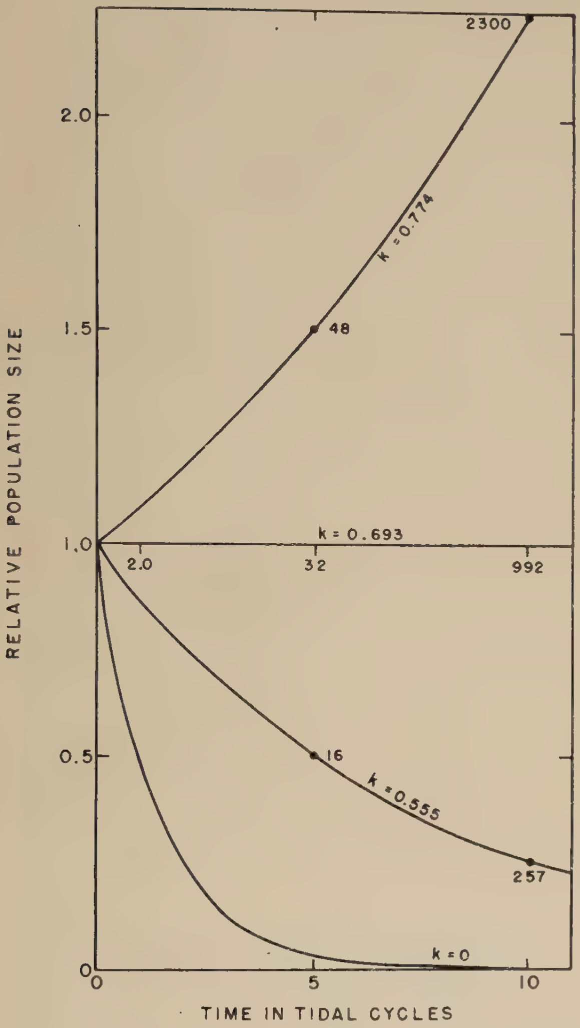

FIG. 1. The effect of the rate of reproduction on the relative size of an endemic population after various times, as tidal cycles, in a segment of an estuary having an exchange ratio of 0.5. The numbers indicate the size the population would have attained if it were not depleted by the circulation.

crease as shown by the lowest curve. This sort of decrease would be expected for a population of larvae released into the segment of the estuary. The horizontal line indicates the population which is just able to maintain itself within the estuary. It will be noted that in this example reproduction must double the population each tidal cycle to balance the removal. During ten tidal cycles reproduction must produce almost a thousand individuals which are lost downstream, although direct observations of the population in the water would indicate no change in population size. The other two lines in this figure indicate the net effect of a reproduction rate greater than, and less than, that required to balance the depletion by the circulation.

It is clear that organisms which can maintain a constant population in some estuaries may be unable to do so in other estuaries where the circulation is more vigorous. For each estuary the rate of reproduction required to maintain a population may be defined in terms of the appropriate exchange ratio, with the results shown in Figure 2. The line drawn in this figure indicates the rate of reproduction required to balance the depletion by the circulation, but does not, of course, indicate what any population will actually do in any estuary. If the growth rate is greater than that required, the population will increase; if less, it will decrease. The average exchange ratios for various estuaries are indicated on this figure.

Moriches Bay, on the south shore of Long Island, has a small exchange ratio and a population should be able to maintain itself with a very low rate of reproduction. In Barnstable Harbor, on the other hand, the tidal exchange is very great, and a population would have to increase rapidly to maintain itself. It is of interest that in the former estuary the population is endemic and characteristic, whereas in the latter the population is strikingly similar to that of the adjacent ocean water outside the limits of the harbor.

In every estuary there must be some region beyond which the organism considered is unable to grow, because of reduced salinity or some other unfavorable condition. The population in this region will not be augmented by new members from upstream, and the foregoing discussion will apply. For all parts of the estuary downstream, however, new members are being introduced into the population from upstream while other members are being carried downstream during each tidal cycle. To take account of both the increment to the population from upstream and loss downstream a different calculation is required. The derivation of the expression for this process has been given by Ketchum, Ayers, and Vaccaro (1952). It is based upon the combination of the equation for the steady-state accumulation of river water in a tidal excursion segment and the growth equation. The former is (Ketchum 1951):

$$Q_n = R\left\{1 + (1-r_n) + (1-r_n)^2 + (1-r_n)^3 + \dots + (1-r_n)^m\right\} \quad (6)$$

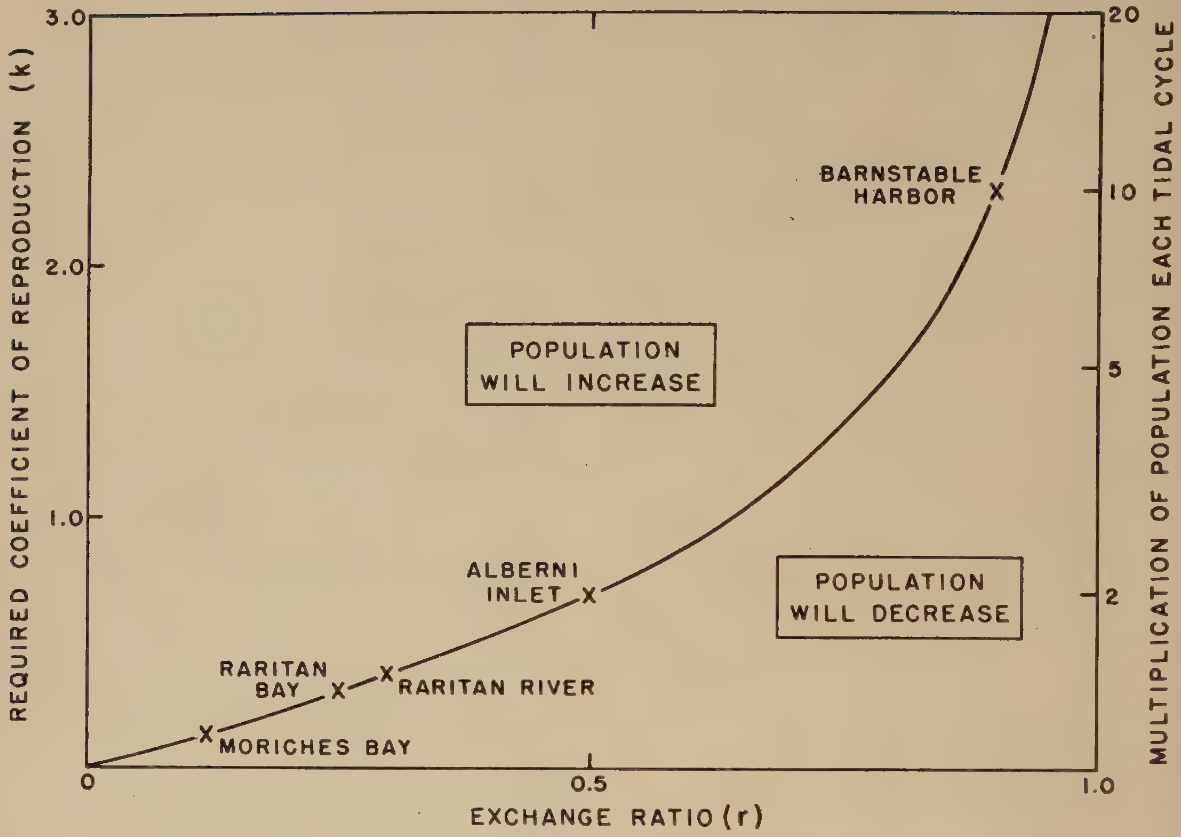

FIG. 2. The coefficient of reproduction required to maintain steady state, endemic populations in estuaries as a function of the exchange ratio.

in which Q_n is the quantity of river water accumulated in the nth tidal excursion segment, and R is the river water introduced to the estuary during a tidal cycle. The combined circulation and growth equation gives:

$$P_n = (P_0)_n \frac{R}{Q_n} \left\{ 1 + (1 - r_n)e^k + (1 - r_n)^2 e^{2k} + (1 - r_n)^3 e^{3k} + \ldots + (1 - r_n)^m e^{mk} \right\} \quad (7)$$

in which $(P_0)_n$ is the increment of population to the nth segment during a tidal cycle, P_n is the steady-state level of population achived as a result of a series of tidal cycles, and the ratio R/Q_n is the exchange ratio, r_n. As the number of tidal cycles becomes large this series approaches:

$$P_n = (P_0)_n r_n \quad \frac{1 - (1 - r_n)^m e^{mk}}{1 - (1 - r_n) e^k} \quad (8)$$

Let us consider what will be the result of such a regime within an estuary. Under these conditions a steady-state population level can be maintained with a variety of rates of reproduction rather than with one alone. For example, if the population did not grow at all within the part of the estuary under consideration the population would nevertheless tend to increase until it approached the size of the population being introduced from upstream, as shown in Figure 3. The rate of reproduction which is necessary to maintain a steady-state endemic population, as discussed above, will theoretically permit the population to increase indefinitely in a location where an increment from upstream is available. Since the reproduction of the population balances the depletion by the circulation, the population will increase by the amount introduced each tidal cycle. To be ecologically more precise, it could be stated that this rate of reproduction would permit the population to increase until crowding or some other factors operated to decrease the reproduction rate.

Any reproduction rate less than that required to maintain an endemic population will produce a steady-state population if increments are also being introduced from upstream. Positive reproduction rates will produce populations greater than the increment from upstream. Even a negative reproduction rate, or in other words an excess of death over reproduction, will permit the attainment of a steady-state population which,

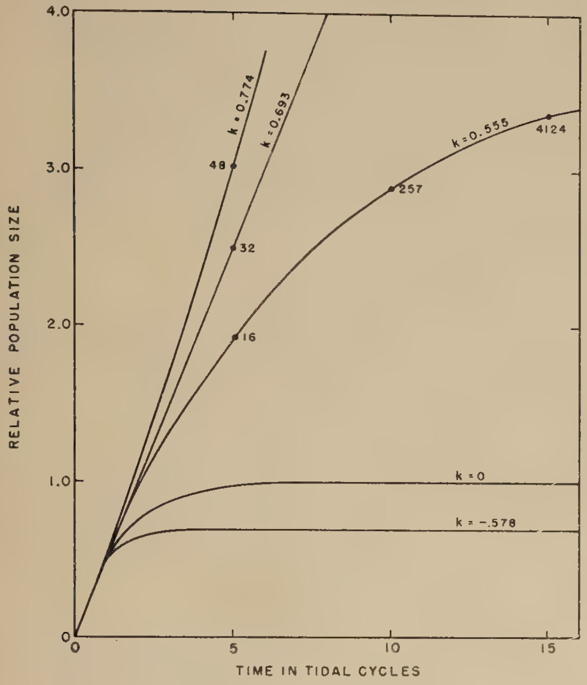

Fig. 3. The effect of the rate of reproduction on the relative size of a population which is being augmented by increments from upstream for various times, as tidal cycles, in a segment of an estuary having an exchange ratio of 0.5. The numbers indicate the size the population would have attained if it were not depleted by the circulation.

however, will always be smaller than the increment from upstream. The steady-state population size under these conditions is given by:

$$P_n = \frac{(P_0)_n r_n}{1-(1-r_n)e^k} \qquad (9)$$

This simplification of equation (8) is valid only when e^k is less than $1/(1-r)$.

It is clear from the foregoing statements that a single simple figure cannot be presented to describe conditions in an estuary where the population is both being augmented from above and decreased by losses seaward. A family of curves is presented in Figure 4 which relate the population size expected after a large number of tidal cycles to the rate of reproduction of populations for estuaries having various exchange ratios. All of the curves cross at a reproduction rate of zero and a relative population size of unity, indicating that the population is the same as that being introduced by the circulation during each tidal cycle. When the reproduction rate is positive, the population developed will be larger in those estuaries with smaller exchange ratios. If, however, the population is dying within the part of the estuary considered, larger populations will be obtained in estuaries having the larger exchange ratios. The reason for this is that the population is present in the estuary for a shorter period of time if the exchange is great, and consequently the population is not so greatly depleted by death.

Reproduction Rates

The foregoing discussion has advanced the thesis that the circulation of the estuary defines the minimum rate of reproduction which will permit the existence of a population in an estuary. It is pertinent to inquire whether populations can be expected to grow at such rates.

For the micro-organisms which reproduce by simple division there is a wealth of information available. Among the bacteria the division rate may be very great and a single cell can, under favorable conditions, produce many thousands of offspring during the course of one tidal cycle. Bacteria can easily replace the depletion resulting from the exchanges if conditions for growth are suitable. Under unfavorable conditions, however, such as are encountered by pollution bacteria in estuaries, the population may fail to grow, or may die at an appreciable rate as a result of the bactericidal action of sea water and predation (Ketchum, Ayers, and Vaccaro 1952). In such cases the circulation has a pronounced effect on distribution.

Some reproduction rates which have been observed with phytoplankton populations are given in Table I. From these rates the relative size of the population after a complete tidal cycle, and the fraction of the population which can be replaced by reproduction during a complete tidal cycle have been computed.[2] This fraction is a direct indication of how vigorous the exchange may be without depleting an endemic population within the estuary. In general it may be said that local phytoplankton populations may be expected to maintain themselves within estuaries where the exchange ratios are about 0.5 or less. Greater exchanges would tend to deplete the population more rapidly than it can reproduce itself.

Most animal populations do not reproduce by simple division, and one may be interested in considering the rate of production of one of the planktonic larval stages, or in the rate of reproduction of the population as a whole. A great deal of basic information is needed before generalizations about the effects of the circulation on various stages of the life cycle of animal populations can be made.

Clarke (1946) and Riley (1947) have analyzed the production of zooplankton populations over Georges Bank. They derive a maximum net production rate of about 5% per day. This is only

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[2] This conversion has been made only for the semi-diurnal tidal cycle of 12.4 hours.

TABLE I. *Some reproduction rates of Phytoplankton populations.*

Population	Time to double	Coefficient of reproduction rate		Relative population after tidal cycle	Fraction replaced per tidal cycle
	days	days^{-1}	tides^{-1}	$\frac{P_m}{P_0}$	$\frac{P_m - P_0}{P_m}$
Phytoplankton 1					
minimum	7.5	0.093	0.047	1.05	0.048
maximum	0.67	1.03	0.53	1.70	0.412
mean	1.38	0.50	0.26	1.30	0.231
Phytoplankton 2					
minimum	1.50	0.46	0.24	1.27	0.213
maximum	0.75	0.92	0.48	1.62	0.383
mean	1.12	0.62	0.32	1.38	0.275
Cultures					
Biddulphia 3	0.42	1.65	0.86	2.36	0.576
Coscinodiscus 4	0.605	1.14	0.59	1.81	0.447
Nitzschia 5	0.58	1.19	0.62	1.86	0.462

[1] Riley *et al.* 1949; 2. Harvey *et al.* 1935; 3. Gran 1927; 4. Jenkin 1937; 5. Ketchum & Redfield 1938.

about half as large as the minimum value given in Table I for phytoplankton populations.

Johnson and Olson (1948) have studied the reproduction of *Tisbe furcata,* a marine harpacticoid copepod. On the average, broods consisting of 57 eggs were produced at intervals of three days. In their experiments there was 80% survival. It can be concluded that two individuals of *Tisbe furcata* can produce 46 viable eggs every three days during the breeding season. The coefficient of the "rate of production" of eggs calculated from these values is 0.522 per tidal cycle, and the fraction of eggs replaced each tidal cycle is 0.408. This is comparable to the rate of reproduction of phytoplankton populations. Johnson and Olson found that the brood of *T. furcata,* however, required between 15 and 31 days to reach maturity. The coefficient of the rate of reproduction of the population as a whole is only 0.106 per tidal cycle for a generation time of 15 days, or about half of that rate for a 31 day period. Thus five to ten per cent of the population can be replaced each tidal cycle.

These estimates of the rate of reproduction of animal populations are admittedly sketchy, but they do indicate, on the whole, that such populations reproduce more slowly than the phytoplankton and are thus less capable of maintaining a unique, endemic population in the upper reaches of the estuary. The planktonic larvae may, however, exhibit vertical migration which could greatly modify their distribution and the effects of the circulation. It would be easy, for example, to postulate that the larvae have a tendency to migrate downwards away from the light and into the more saline water. This would place them in the counterdrift and transport them up the estuary. Such a migration would clearly lead to a higher concentration of the larvae than is calculated from the exchanges of river water. Altogether too little is known about the physiology and rate of production of various stages of the larvae and rate of reproduction of the population as a whole to permit any definite conclusions concerning the importance of the circulation in their life cycle.

APPLICATION TO NATURAL CONDITIONS

From the foregoing theoretical considerations it appears that different sorts of populations may be expected in natural estuaries solely as a result of the vigor of the circulation. A few examples may serve to clarify the general application.

An endemic phytoplankton population, consisting of small chlorophytes, develops year after year in Moriches Bay, Long Island, New York (Fig. 5). During the summer months these algae are the predominant members of the phytoplankton population within the bay, though they are rare or absent in nearby waters. The bay is heavily fertilized by drainage from duck farms around the banks of the tributary rivers.

The circulation is slow, and only about 12% of the volume of water present in any tidal excursion segment is exchanged during a tidal cycle. For the bay as a whole the rate of exchange is only about a tenth of this value.

Ryther (1954) has shown by physiological experiments on pure cultures of these algae that they are uniquely suited to grow under the conditions found in Moriches Bay. They are able to grow in nearly fresh water, and optimum growth was obtained in salinities indicative of about 50% sea water. The temperature of the bay water is at or near the optimum (25° C.) for their growth most of the summer. The proportion of phosphorus to nitrogen in the duck farm wastes is close to the optimum ratio for these species.

This is clearly a case of rapid multiplication of a population which is uniquely adjusted to the ecological conditions which exist in the upper, less saline part of the estuary. The slow rate of the circulation permits the accumulation of a large population which is thus placed in a favorable competitive position and maintains superiority in numbers over large areas.

The effect of a rapid circulation on the dispersal of planktonic larvae may be inferred from investigations which have been made in Barnstable Harbor, Cape Cod, Mass. (Fig. 6). As shown by Ayers (unpub.) the exchange ratio for each tidal excursion segment is about 0.9, and for the harbor as a whole the rate of exchange is about one third of this value. The brackish-water planktonic

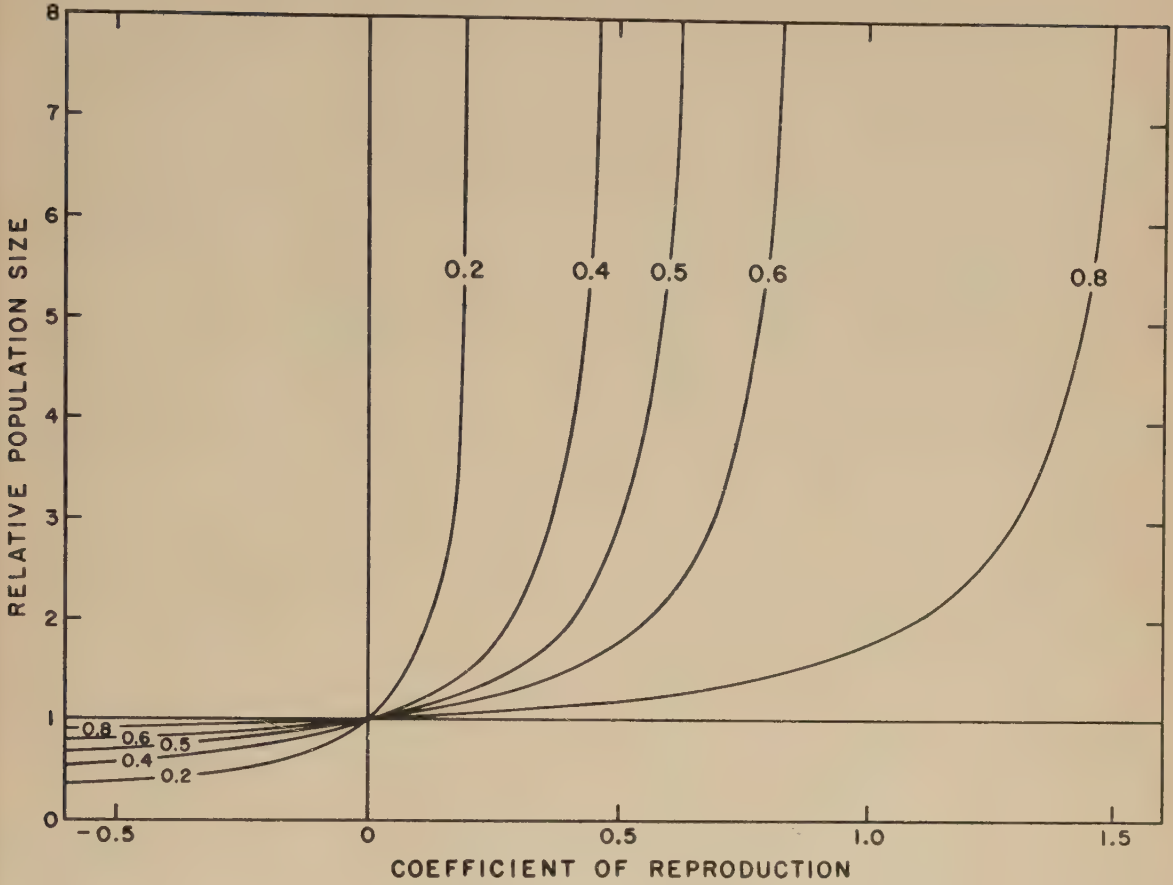

FIG. 4. The relationship between the steady-state size of a population and the coefficient of reproduction for estuaries characterized by various exchange ratios.

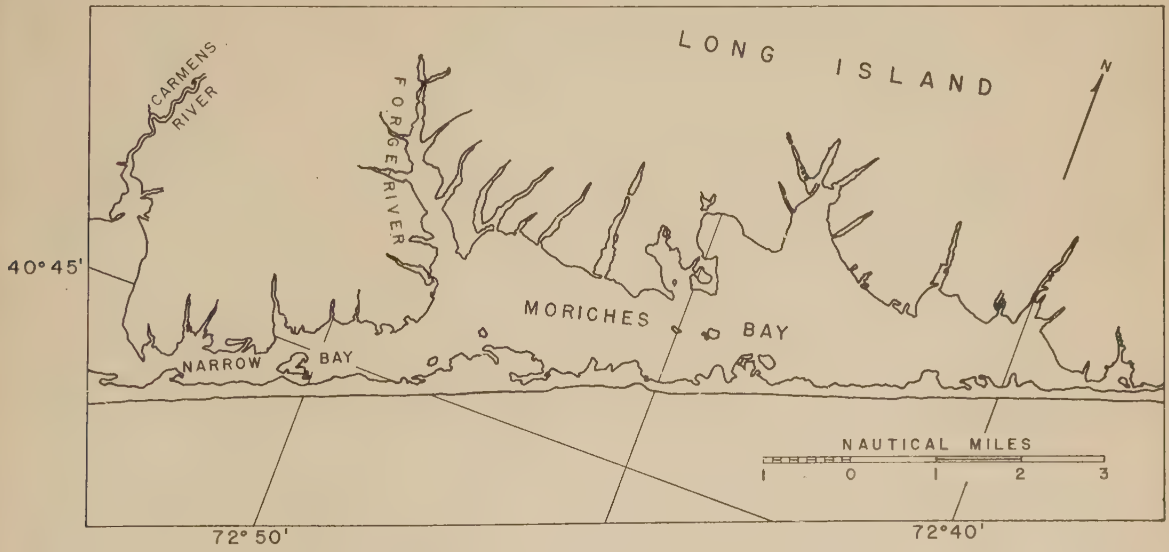
LONG ISLAND
N
CARMENS RIVER
FORGE RIVER
MORICHES BAY
NARROW BAY
40°45'
NAUTICAL MILES
1
0
1
2
3
72° 50'
72°40'

FIG. 5. Moriches Bay on the South Shore of Long Island, New York. The mean tidal range is about 0.4 feet and the average exchange ratio is about 0.12.

forms, therefore have very little opportunity to establish dominance, since they would have to multiply at enormous rates in order to maintain the population. It is not surprising, therefore, that in this location the planktonic population is similar to that of the adjacent ocean waters.

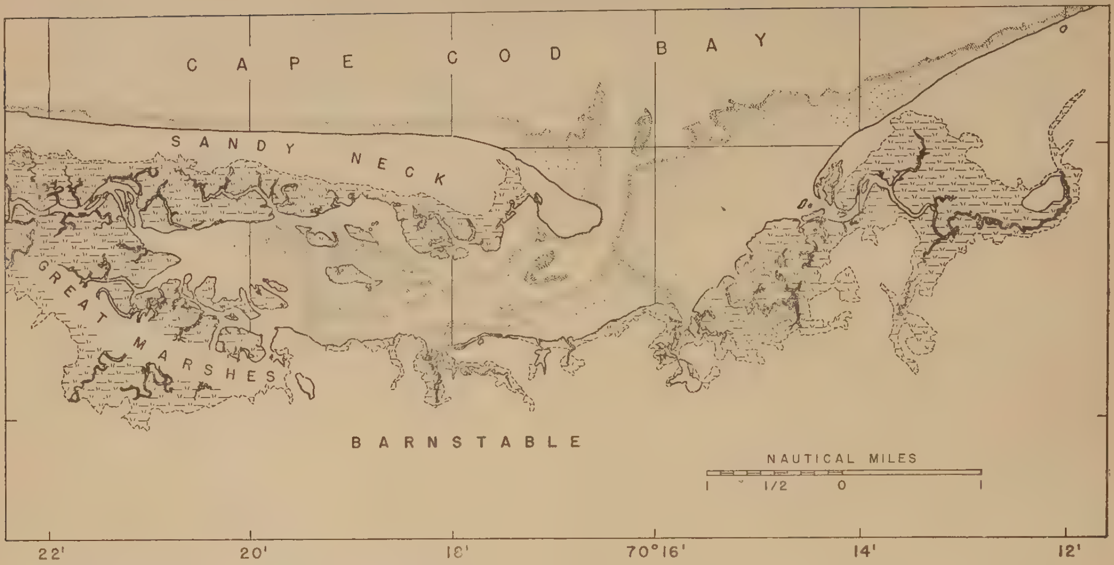

FIG. 6. Barnstable Harbor on the North Shore of Cape Cod, Mass. The mean tidal range is eleven feet, and the average exchange ratio is 0.9.

One of the interesting problems in Barnstable Harbor is that the clam population has decreased to negligible proportions and, as shown by Turner (1949, 1950), efforts to re-establish it have been largely unproductive. According to Belding (1930) a pair of two and one half inch clams can produce about three million larvae, which have a pelagic life of about fourteen days or twenty-eight tidal cycles. From the average exchange ratio of Barnstable Harbor as a whole (0.30) is can be calculated that, as a result of circulation alone, neglecting larval mortality, about 150 spat would be the most which could remain for each pair of clams. Ayers (unpub.) has concluded that mortality between spatfall and maturity alone would leave less than one mature clam annually to replace the population, and considering the possible decimation of larvae by predation and mortality it is not surprising that only rarely indeed is a substantial set obtained.

The distribution of coliform bacteria in the Raritan River estuary is an example of the changes in a population which is both augmented and depleted by the circulation, while being subject to biological changes. In this case the population is introduced at the freshwater end of the estuary at a high level and a nearly constant rate by the sewage effluents of the city of New Brunswick and other municipalities upstream. Because of the bactericidal effect of sea water, the population is dying off as the circulation carries it downstream. The total population decreases by about 100,000 cells/ml. over a ten mile length of the estuary. We found that by taking account of the circulation, of the rate of bactericidal action of sea water, which was measured under laboratory conditions independently, and of the predation resulting from the zooplankton population in the river, we could account for more than 99% of the observed decrease (Ketchum, Ayers, Vaccaro 1952). A correct interpretation of the observed distribution could be obtained only when both the biological processes and the circulation were taken into account.

The final example is drawn from the unpublished work of Barlow (1952) who has studied the zooplankton population of a small estuary, Great Pond, near Woods Hole, Mass. (Fig. 7). Barlow observed that *Acartia tonsa* was apparently endemic in the estuary during the early summer, since maximum numbers of both nauplii and copepodid larvae were found near the head of the main pond where the salinity was about 10-20 parts per thousand. These populations were maintained at high concentrations for weeks in spite of the continuous depletion by the circulation.

The rate of production of these larvae was calculated from the natural distribution by equation 8, and was also determined from experiments in which samples of the water were isolated from the circulation in several 5-gallon jugs which were re-suspended in the estuary. Throughout most of the estuary the rates of production of both nauplii and copepodid larvae as determined by the two independent methods were in close agreement. Both sets of data showed a decrease in the rate of production of larvae with increasing salinity. In the part of the estuary where the salinity was about 10 parts per thousand the production rates indicated that the population of larvae could dou-

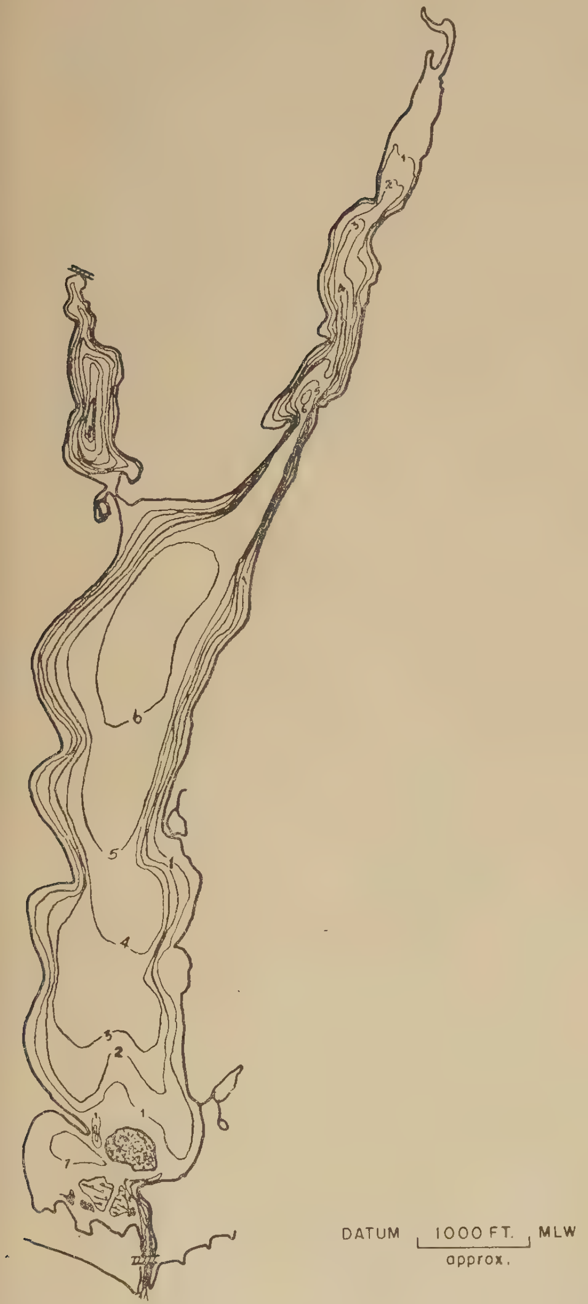

FIG. 7. Great Pond near Falmouth, Mass. The depth contours are shown in feet at mean low water. The mean range of tide is 1.5 feet, and the average exchange ratio is 0.30.

ble in less than a day. This rate of production was necessary to maintain the high population level observed in this region. Near the mouth of the estuary, where salinities were 30 parts per thousand, the larvae had negative production rates which would reduce the population to about a half of its original value in slightly less than one day. In this region the low population was maintained by augmentation from upstream. In the freshest part of the estuary the rate of production obtained in the jug experiments was too low to account for the observed distribution—a discrepancy which Barlow attributes to the recruitment to the population from the deeper water downstream.

The larvae are, of course, only stages in the development of *Acartia tonsa.* The rates of production depend on the rate of production of eggs by the adult and the rate of their development. The negative values in the saltier parts of the estuary are not necessarily indicative of mortality, since similar results could be obtained because of the metamorphosis of the nauplius to the copepodid and of the copepodid to the adult. The importance of these observations is that Barlow has shown that production rates derived from observed distributions in an environment complicated by an active circulation of water are comparable to the rates obtained in a similar environment isolated from the circulation.

SUMMARY

1. The rate at which a planktonic population must reproduce in order to maintain itself in an estuary is determined by the vigor of the circulation. The reproduction rate required for an endemic population is defined in terms of an exchange ratio determined as the proportion of water escaping seaward each tidal cycle.

2. If a population is augmented from upstream as well as depleted by the circulation, a steady-state population will be achieved at a level determined by the rate of reproduction and the rate of the circulation. A method for determining the size of the population expected under various conditions is presented.

3. Examples of the application of these calculations in various estuaries are presented for a bacterial population, a phytoplankton population, the planktonic larvae of a sedentary population, and larvae of a zooplankton population.

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Contribution No. 614

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THE BINDING OF COPPER BY HEMOCYANIN

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(Contribution No. 614)

TWO FIGURES

Many marine animals accumulate remarkably large amounts of copper from sea water, producing a concentration of copper within their bodies far exceeding that in their external environment (Redfield, '34). The horseshoe crab, *Limulus polyphemus,* and the sea conch, *Busycon canaliculatum,* are among the marine animals which can accomplish this. They produce blue-colored respiratory pigments, known as hemocyanins; these carry nearly all of the copper found in their bodies.

Kobert (Kobert, '03) first observed that the addition of cyanide to oxygenated hemocyanin (oxyhemocyanin) results in the release of oxygen, and the decolorization of the protein. Kubowitz ('38) showed that this decolorization was due to the ability of the cyanide to form a complex with the copper ions, removing them from the protein. Previous to the work of Kubowitz, Pearson ('36) had attempted to explain the decolorization by postulating the formation of a protein-cyanide complex, or cyano-hemocyanin. An equilibrium constant was calculated for the postulated reaction. In view of Kubowitz's discoveries, it seems reasonable to calculate instead an equilibrium constant for the dissociation of copper from hemocyanin.

Such a constant has been calculated from a series of experiments in which cyanide, which has a known affinity for cuprous ion, is allowed to compete with the protein for the metal.

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METHODS

The unpurified sera of both *Limulus polyphemus* and *Busycon canaliculatum* were used in these experiments, since the protein consists in each case of at least 90% pure hemocyanin (Redfield, '28 and Montgomery, '30). The serum was obtained by allowing the whole blood to stand until the white cells had coagulated. The clear blue solution was then poured off and filtered. Copper analysis was performed colorimetrically. Three milliliters aliquots of the serum were wet-ashed with concentrated sulfuric acid and Superoxol. Color was developed in the resultant solution by the addition of sodium diethyl dithiocarbamate, using a slight modification of a standard procedure (Price and Telford, '50). The method gave reproducibility of better than 0.5%.

The oxyhemocyanin concentration was determined spectrophotometrically (Pearson, '36). Measurements of the *Limulus* serum were made at 590 mμ, and of *Busycon*, at 570 mμ. A Beckman model DU Quartz Spectrophotometer was used. pH measurements were made with a Beckman Model G pH meter, with use of a dipping glass electrode. The cyanide solutions were standardized against silver nitrate solution of known concentration (Kolthoff and Sandell, '48).

In each set of experiments, a constant amount of serum was mixed with increasing quantities of potassium cyanide solution, and made up to volume with either buffer or water. The mixtures were allowed to stand, stoppered, at room temperature, until no further change could be observed in the extinction coefficient (generally 24 hours at 25–28°C.). The solutions were centrifuged before being read in the spectrophotometer.

THEORETICAL

It is easy to see, qualitatively, that the binding of the copper to the protein must be relatively strong. Pearson found that a large excess of cyanide over copper had to be added to produce complete decolorization. We found that the addition of 100 moles of imidazole per mole of copper produces no decolorization, although imidazole has an affinity for copper as strong as that of ammonia (Gurd, Edsall, Felsenfeld and Goodman, '52).

The complexity of the protein molecule makes it necessary to simplify the picture of this competition as much as possible. The protein molecule is assumed to consist of a number of identical reactive groups or sites, denoted below by the letter R, each of which is capable of binding a maximum of two copper ions. The assumption is made that pairs of copper ions on the same site interact, but that copper ions on different sites behave independently. This model for the protein molecule seems reasonable in view of the one-to-one ratio of oxygen atoms to copper atoms in oxyhemocyanin. It has been suggested that an oxygen molecule "bridges" a pair of copper atoms (Rawlinson, '41). This would require that pairs of copper atoms be situated close together in the molecule, leading to a much stronger interaction between the pair of copper atoms of any given site than between those belonging to different sites. It has been shown [1] that if copper ion in excess is added to native hemocyanin, it will be bound only weakly by the protein. This indicates that in hemocyanin, the binding sites discussed in this paper are saturated with copper.

The approximation is made throughout this paper that concentration and activity are equal. The reactions which are assumed to occur, and their corresponding equilibrium constants, are:

$$RCu_2O_2 = RCu_2 + O_2 \qquad K_o = \frac{(RCu_2)(O_2)}{(RCu_2O_2)} \qquad (1)$$

$$RCu_2 = RCu + Cu^+ \qquad k_2 = \frac{(RCu_2)}{(Cu^+)(RCu)} \qquad (2)$$

$$RCu = R + Cu^+ \qquad k_1 = \frac{(RCu)}{(R)(Cu^+)} \qquad (3)$$

$$Cu^+ + 2CN^- = Cu(CN)_2^- \qquad k_B = \frac{(Cu^+)(CN^-)^2}{(Cu(CN)_2^-)} \qquad (4)$$

The first assumption made is that the copper in reduced hemocyanin is in the form of cuprous ion. Kubowitz's experiment provides convincing evidence for this. He was able to reactivate protein from which copper had been removed, only by the addition of cuprous ion, and not by the addition of cupric ion. Hemocyanin, in the deoxygenated state, completely lacks the blue color characteristic of cupric complexes. It should be noted that no assumption is made about the oxidation state of copper in oxyhemocyanin.

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[1] I. Klotz, personal communication.

The concentration of reduced hemocyanin, RCu_2, was calculated from the measured concentration of oxyhemocyanin, RCu_2O_2. The constant K_o used in these calculations was taken from previously published data on oxygenation (Redfield, '30, and Redfield and Ingalls, '33). In each case a single constant was used to describe the oxygenation curve. This was necessary because the pairs of constants given by Redfield and Ingalls only fit the curve at relatively low oxygen pressures, where there is considerable deviation from hyperbolic form. At higher pressures, at which the various curves probably coincide quite closely with the hyperbolic case, the constant for the hyperbolic curve was used. This seemed to be justified by the reasonably good consistency of the results obtained from this method and those from experiments with deoxygenated serum, where the oxygen constant was not involved in the calculation.

Equations 2 and 3 assume that the copper dissociates from the unoxygenated hemocyanin only, and that we may neglect the possible existence of the species RO_2. This assumption was justified by an experiment which showed that the amount of copper removed from the protein depends upon the concentration of unoxygenated hemocyanin. In this experiment, concentrations of reduced hemocyanin were increased by the reduction of the partial pressure of oxygen. By the use of a water aspirator, oxygen was removed from samples of serum placed in small suction flasks. A few drops of capryl alcohol were added to prevent foaming. When maximum decolorization had been achieved, the flasks were filled with nitrogen, and the desired quantity of cyanide solution added through the nitrogen atmosphere. The flasks were quickly re-evacuated, and allowed to stand in such a condition for several hours, until the final readings to be described indicated that equilibrium had been reached.[2] When air was readmitted, some blue color returned, but the extinction coefficient was much lower than that obtained by performing the same experiment in air, using the same quantities of serum and cyanide. The color intensity increased very slowly on exposure to air (a few days for detectable changes), and it was therefore possible to use the extinction coefficient as an indication of the equilibrium position in vacuum, assuming that the introduction of oxygen disturbed the equilibrium extremely slowly. The fact that decolorization is so much greater when large quantities of reduced hemocyanin are present indicates that the loss of oxygen must involve a considerable decrease in the copper binding constant — a phenomenon which seems to be quite similar to one observed by Joselow and Dawson ('51) for the copper enzyme ascorbic acid oxidase. This decrease is, in fact, demanded by thermodynamic considerations if the oxygen-carrying properties of the protein are completely destroyed by removal of copper.

The final assumption concerning the copper dissociation, that $k_2 >> k_1$, is equivalent to saying that the concentration of the species RCu, where the copper exists alone on a given site, is negligible in the first approximation. Such a postulate leads to the calculation of two association constants, with $k_2 >> k_1$, so that the assumption leads to a consistent answer. No other assumption yields a consistent conclusion, since the data is more than sufficient to determine the two constants uniquely.

The copper-cyanide reaction is assumed to go as far as the formation of the double cyanide complex, but no further. Where large excesses of cyanide were present, allowance for the formation of the triple complex did not make significant changes in the calculated results. The value used for the constant, $k_B = 10^{-23}$, is the one given by Bjerrum ('50). Its somewhat doubtful accuracy is one of the limiting factors in the accuracy of the results obtained. Because of the inaccuracy of K_o and k_B, and the errors of measurement, the error of the constants calculated in this paper is probably of the order of ± 1.0 in logarithms.

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[2] Equilibrium was attained much more rapidly under these conditions than it was when the experiments were performed in air. The relative rapidity of the initial rate of dissociation, compared with the rate of recombination of copper and protein, suggests that the dissociation rate must slow down considerably when the equilibrium point has been nearly reached.

Using the treatment of Scatchard ('49), Klotz ('46), and others, we first define [3] a quantity ν,

$$\nu = \frac{\text{copper bound to reduced hemocyanin}}{\text{total sites on reduced hemocyanin}}$$

ν has a maximum value of 2. For these experiments,

$$\nu = \frac{2 \times (RCu_2)}{(R) + (RCu_2)}$$

The intrinsic constant for the copper-protein reaction (the reaction of copper with one of the two "spots" on a given site, regardless of whether the other "spots" are occupied), is given by

$$k = \frac{\nu}{(2 - \nu)\ (Cu^+)}$$

If log k is plotted against ν, extrapolation to $\nu = 0$ will give the logarithm of the first constant, while extrapolation to $\nu = 2$ will give the logarithm of the second constant. These must be statistically corrected (here, by adding and subtracting log 2 for k_1 and k_2, respectively), to give the true constants defined in equations 2 and 3. The method is therefore as follows:

1. The concentration of $RCu_2\,O_2$ is calculated from spectrophotometric data.
2. The concentration of RCu_2 is calculated from the oxygenation constant.
3. The concentration of R is found knowing $RCu_2\,O_2$, RCu_2, and the total copper in the protein.
4. The concentration of $Cu\,(CN)_2^-$ is calculated from the quantity of R present.
5. The concentration of CN^- is calculated from the total cyanide added, the value of $Cu\,(CN)_2^-$, the value for the dissociation constant for HCN, 7.2×10^{-10}, and the pH.

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[3] The symbol ν is equivalent to the symbol $\bar{\nu}$ of Scatchard ('49).

6. ν, Cu^+ and k may then be calculated from the above formulas. When the vacuum-nitrogen route is used, it is possible to measure the concentration of RCu_2 directly. It is equal to the amount of oxyhemocyanin formed when oxygen is admitted.

7. k_1 and k_2 are calculated from k as described above.

RESULTS

Table 1 gives the results of the first series of experiments on cyanide competition in air. Two milliliter samples of *Limulus* serum were treated with varying amounts of KCN solution, and the mixtures made up to a total volume of 12 ml with borate buffer. The buffer is made by the addition of solid sodium hydroxide to a 0.1 M solution of H_3BO_3, to give a pH of 8.31. In all of the experiments described in this paper, the partial pressure of oxygen was taken as 159.5 mm of mercury and the oxygenation constant K_o for *Limulus* hemocyanin, was taken equal to 0.32 for pH greater than 8, and as 0.40 for pH equal to or less than 8 (Redfield, '30).

TABLE 1

Limulus serum, buffered in the region of pH 8.1
KCN concentration: 7.12 × 10^{-3} M.
Copper concentration in all final solutions: 0.388 mM.

KCN CC. ADDED	OXYHEMOCYANIN %	pH	ν	LOG k
0	100.0	7.90	. . .	. . . .
1.00	99.0	7.96	. . .	. . . .
2.00	94.0	8.00	0.392	18.91
3.00	80.4	8.02	0.158	18.17
4.00	62.8	8.07	6.60×10^{-2}	17.80
5.00	37.2	8.10	2.31×10^{-2}	17.33
6.00	19.1	8.12	9.24×10^{-3}	16.97
7.00	8.0	8.17	3.42×10^{-3}	16.95
8.00	6.5	8.23	2.73×10^{-3}	16.86

Extrapolation of the curve to $\nu = 0$ (fig. 1, solid circles) gives for the association of the first copper ion an intrinsic constant (i.e., statistically uncorrected) of $10^{16.7}$, and a corrected constant, k_1, of $10^{17.0}$. This curve does not permit extrapolation to $\nu = 2$, so that it is impossible to determine k_2 directly from the data of table 1.

Table 2 shows the results of a similar experiment with *Busycon* serum. Four milliliter samples of serum were used, and made up to a total volume of 12 ml with KCN and the borate buffer described above. The oxygenation constant was

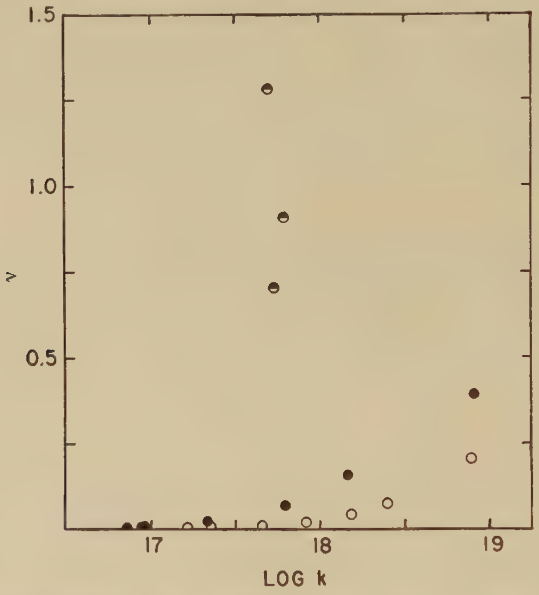

Fig. 1 Intrinsic constants, uncorrected for proton affinity. Legend: pH 8.1 ●; pH 8.8 ○; vacuum ◓.

TABLE 2

Busycon serum, buffered in the region of pH 8.1
KCN concentration: 7.12 × 10^{-3} M.
Copper concentration in all final solutions: 0.501 mM.

KCN CC. ADDED	OXYHEMOCYANIN %	pH	ν	LOG k
0	100.0	7.96	. . .	. . . .
1.00	86.7	8.03	0.118	17.01
2.00	62.7	8.08	3.02×10^{-2}	16.47
2.50	58.8	8.08	2.56×10^{-2}	16.61
3.00	48.5	8.11	1.69×10^{-2}	16.60
3.50	40.8	8.13	1.25×10^{-2}	16.56
4.00	36.9	8.15	1.06×10^{-2}	16.64
5.00	33.9	8.21	9.28×10^{-3}	16.91

assumed to be 0.70 (Redfield and Ingalls, '33). A value of $10^{16.8}$ at pH 8.3 was obtained for k_1 in *Busycon* hemocyanin, indicating that there is no striking difference between the behavior of the *Busycon* hemocyanin and that of the *Limulus*.

A somewhat different result was obtained from *Limulus* serum when the pH was increased to 8.7. In this experiment, a borate buffer adjusted to a pH of 8.88 was used. The KCN solution was diluted 1:1 with this buffer, and the resultant cyanide solution added to 1 ml portions of the serum. The mixtures were made up to a total volume of 12 ml with a solution of the original borate buffer diluted 1:1 with water. The results, shown in table 3 and figure 1, open circles, give a value for the true k_1 at pH 8.7 of $10^{17.4}$, a significant increase over the value obtained at pH 8.0. This increase is significant even though the estimated error for the final answer is considerably larger, since the major part of the error is introduced through the uncertainty in choice of constants mentioned above.

TABLE 3

Limulus serum, buffered in the region of pH 8.7
KCN concentration (buffered): 3.56×10^{-3} M.
Copper concentration in all final solutions: 0.194 mM.

KCN CC. ADDED	OXYHEMOCYANIN %	pH	v	LOG k
0	100.0	8.69	...	....
1.00	97.5	8.69	...	....
2.00	83.1	8.70	0.203	18.89
3.00	65.3	8.70	7.47×10^{-2}	18.39
4.00	49.2	8.71	3.89×10^{-2}	18.18
5.00	33.1	8.72	1.97×10^{-2}	17.92
6.00	17.8	8.73	8.58×10^{-3}	17.66
7.00	7.6	8.76	3.24×10^{-3}	17.36
8.00	4.2	8.77	1.71×10^{-3}	17.22

The change in the value of k_1 with increasing pH suggests that the group on the protein which binds the copper ion is capable of binding hydrogen ion. An amino, sulfhydryl, or imidazole group, among others, would behave in such a manner. In the calculations made above, it has been assumed that each site, R, which had no copper ion attached to it, would be capable of recombining with copper ion. One must now take into account the existence of another species, RH^+, which reduces the amount of free R available for recombination. This results in competition between hydrogen and copper ions for a place on the protein.

The correction for hydrogen ion dissociation requires a more detailed specification of the protein model. If, for example, a single group, such as a sulfhydryl group, holds each copper ion, then the species RH^+ and RH_2^{++} are possible; if a pair of amino groups holds each copper ion, then all of the species from RH^+ to RH_4^{++++} might exist. Many such models were tried. It was found that none gave better results in the procedure to be described than the simple model in which only one hydrogen ion could be attached to each site. Such behavior is consistent with models of the sulfhydryl type, provided that the acid association constant for the formation of RH^+ is much larger than the constant for the formation of RH_2^{++}, so that the concentration of the diprotic species is negligible. This is usually true for a dibasic acid in which the sites of bound hydrogen are fairly close together.

By assuming the existence of a species RH^+, and trying different values for an acid dissociation constant,

$$k_A = \frac{(R)\ (H^+)}{(RH^+)}$$

one can estimate a value for k_A, since the new copper constant k_1' should be independent of pH when a proper value of k_A is chosen. By such a procedure, it was found that a value of pk_A of about 10.0 allows the data of tables 1 and 3 to be reinterpreted so that the curves now extrapolate (fig. 2) to a common point at $\nu = 0$. From these curves one finds a statistically corrected value for k_1 of $10^{18.7}$, and for k_2, of $10^{20.5}$. This is in agreement with our assumption that $k_2 >> k_1$. A theoretical curve, using these values, has been drawn for comparison. It is not possible to make the two sets of experimental points, or the theoretical curve, coincide entirely by the choice of a single acid constant, very possibly due to electrostatic corrections which are not made in this paper, and which might become more important as more charged copper ion is attached to the protein (i.e., for large ν). No explanation is offered here for the apparent positive interaction in the complexing of the second copper. It may be, in part, the result of the choice of the model for copper dissociation (i.e., pairs of copper ions interacting).

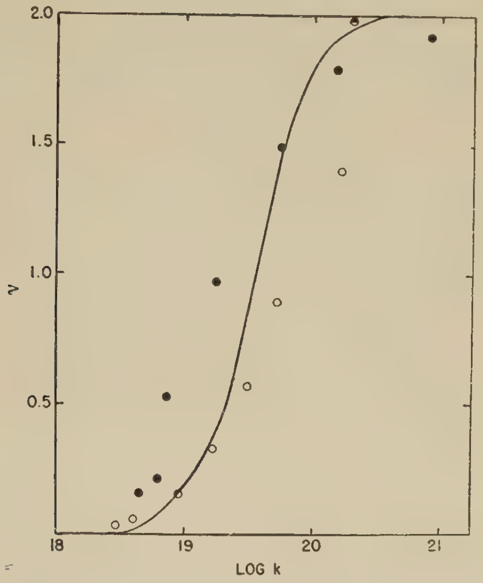

Fig. 2 Data of figure 1 corrected for proton affinity. The solid line is the theoretical curve calculated from the final values of the equilibrium constants. (Legend same as for fig. 1.)

Since the model chosen to make the correction for acid dissociation is an arbitrary one, the value obtained for pk_A may seem to be equally arbitrary. However, all of the models which showed any tendency to bring together the extrapolation points of the two curves did so in the region of $pk_A = 10$, so that there is reason to believe that this value is fairly independent of the model chosen.

The ionic strengths of the solutions of tables 1 and 3 differ somewhat. If we calculate the ionic strength of sea water from the average concentration of ions (Henderson, '13), we obtain a value of 0.67. It is known that *Limulus* serum possesses a salt concentration similar to that of sea water (Krogh, '39). This enables us to estimate the ionic strength of the solutions of tables 1 and 3. They are 0.08 and 0.11 to 0.12 respectively. It seemed possible that such a difference in ionic strength might account for the differences between the two curves of figure 1. A set of experiments was performed in which the ionic strength was raised to 0.22, and the pH varied (without buffer) by the addition of CN^-. The resulting points coincided exactly with the curve of table 1 where the pH was about 8.1, and with the curve of table 3 where the pH was about 8.6. This indicates that the pH, not the small variation in ionic strength, is the primary factor influencing the position of the curves.

TABLE 4

Limulus serum, equilibration in absence of oxygen
KCN concentration: 7.12×10^{-3} M.
Copper concentration in all final solutions: 0.388 mM.

KCN CC. ADDED	OXYHEMOCYANIN %	pH	v	LOG k
2.00	63.9	7.37	1.28	17.70
3.00	45.4	7.58	0.907	17.79
4.00	35.1	7.78	0.701	17.73

Table 4 and figure 1 show the results of the experiments performed in vacuum, which were described at the beginning of this paper.[4] The uncorrected data are not at all in agreement with the other data of figure 1. When the points are recalculated with the inclusion of the acid constant, however, there is good agreement with the other experiments (fig. 2). The point obtained in vacuum shown in figure 2 represents that point with the lowest value of v. The other points had such high corrected values of v (greater than 1.99) that it was impossible to obtain an accurate value of k by calculation. The point given therefore represents a lower limit for the value of k given by the vacuum data alone.

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[4] These experiments used 2 ml of serum, with water and KCN added to make a total volume of 12 ml. No buffer was used.

DISCUSSION

The validity of this analysis depends upon the reversibility of the dissociation of copper from the protein. Although no direct demonstration of complete reversibility has been obtained, several observations seem to indicate that the reaction is reversible. Pearson ('36) attempted to demonstrate the reversibility of the cyanide-hemocyanin reaction by treating the decolorized mixture with oxygen under pressure. His results were negative, for obvious reasons. He also allowed decolorized specimens to remain in contact with air in such a way that HCN could escape, and looked for an increase in the blue color. His results here, too, were negative. A repetition of the latter experiment shows that if the material is allowed to stand for a period of about two weeks, it will begin to regain its color. The work of Kubowitz ('38), in addition, demonstrates that it is possible to replace the copper on the protein and regain 50% of the physiological activity. Kubowitz was never able to regain all of the original activity, probably because of the rather harsh treatment accorded the protein in replacing the cuprous ion. Even if the other 50% of the protein had been inactivated at the binding sites by the large excesses of cyanide, the fact that 50% of the activity remains indicates that the value of k_1 could at worst be too small by a factor of two. This would increase log k_1 to 18.7, which in no way invalidates the conclusion drawn in this paper. The absence of abrupt changes in the direction of the curves suggests that there is actually very little inactivation during the removal of the copper.[5]

The very slow rate of recombination of protein with copper observed in the experiments with deoxygenated hemocyanin has made it impossible to reach the equilibrium position from both directions. It is consequently not possible to state with certainty that the equilibrium position has been reached in the experiments performed with oxygenated hemocyanin. Though the extinction coefficient of the protein solutions appeared to remain constant for some days, it is possible that a very slow dissociation reaction was occurring. The close agreement of dissociation constants calculated from experiments on both sides of the equilibrium position reassures us that the error is not a very large one.

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[5] Experiments of Lessiau, et al., on horse serum albumin ('48) suggest that possible irreversible effects of cyanide on the non-specific portions of the protein molecule, such as reduction of disulfide linkages, are of negligible importance at the cyanide and hydrogen ion concentrations used in removing the copper from hemocyanin.

In *Limulus* and *Busycon* sera at least 90% of the protein is hemocyanin. The other proteins present do not appear to carry any copper (Montgomery, '30). The presence of any impurity in the serum should, therefore, have very little effect upon the resultant constants.

The high value of the equilibrium constant for the addition of the first copper to each site is not similar to that of any simple cuprous complex, with the exception of cuprous-sulfhydryl complex (Bjerrum, '50). Stricks and Kolthoff ('51) have found a value of 1.5×10^{19} for the cuprous-cysteine association constant. Furthermore, the value of 10 for pk_A is consistent with sulfhydryl group behavior. A pair of amine groups would probably bind copper ion with a similar strength, however, so that the results do not indicate conclusively that a sulfhydryl group is involved. The possible existence of a prosthetic group which is composed of structures not directly part of amino acid side chains must not be overlooked.

The author gratefully acknowledges the advice given him by Dr. Alfred C. Redfield throughout the course of this work. He also is indebted to Dr. Margaret J. Hunter for her suggestions and assistance, and to Dr. Linus Pauling, Dr. Walter L. Hughes, Dr. Irving Klotz and Dr. Martin Karplus for helpful discussions. The author thanks the Woods Hole Oceanographic Institution for providing a fellowship, during the tenure of which this work was carried out.

SUMMARY

The binding of copper ion by *Limulus* and *Busycon* hemocyanins has been studied, by allowing cyanide ion to compete for the copper.

The pH-independent constant for the binding of the first copper ion to a site on *Limulus* hemocyanin has been found to be approximately $10^{18.7}$. The constant for the second copper ion is about $10^{20.5}$. *Busycon* hemocyanin has a first constant of approximately $10^{16.8}$, at a pH of about 8.1. In the case of *Busycon,* no attempt was made to determine a true, pH-independent, constant.

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Contribution No. 635

Transactions, American Geophysical Union Volume 35, Number 5 October 1954

VAPOR PRESSURE OF SEA-SALT SOLUTIONS

A. B. Arons and C. F. Kientzler

(Contribution No. 635 from the Woods Hole Oceanographic Institution)

Abstract--Vapor pressures of sea-salt solutions at temperatures between freezing and 25°C are reported and are tied in with previously reported measurements of Higashi made at temperatures between 25 and 175°C.

Introduction--Although HIGASHI and Others [1931] have published measurements of vapor pressure of sea-salt solutions, these were obtained at temperatures from 25 to 175°C, and no direct experimental values have been available for temperatures between freezing and 25°C.

Recent work on atmospheric sea-salt nuclei [WOODCOCK and GIFFORD, 1949], as well as studies of sea fogs and of clouds in which temperatures are above freezing, requires accurate knowledge of vapor pressure in the lower temperature range; and an experimental program of vapor-pressure measurement was consequently undertaken.

Apparatus and preparation of samples--The experimental technique used was a modification of that reported by GIBSON and ADAMS [1933]. A schematic diagram is shown in Figure 1, and a

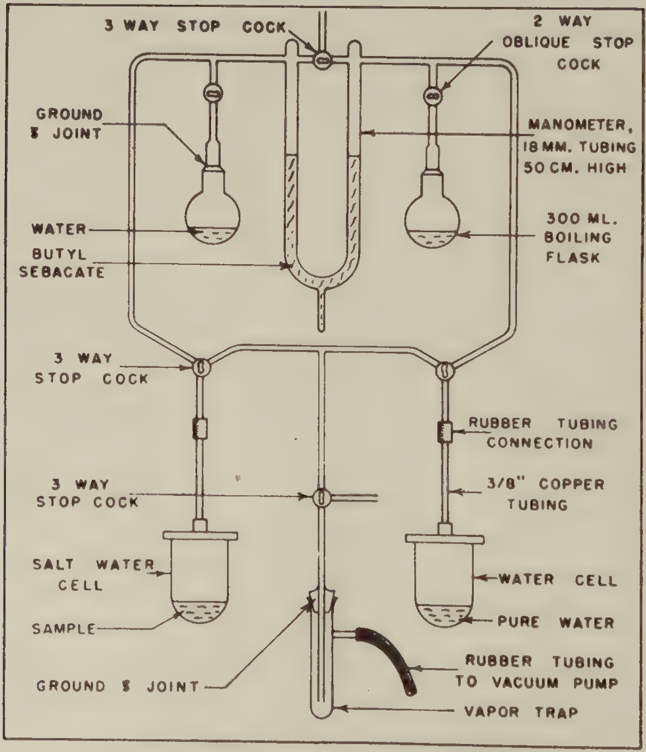
3 WAY STOP COCK
2 WAY OBLIQUE STOP COCK
GROUND § JOINT
MANOMETER, 18 MM. TUBING 50 CM. HIGH
WATER
300 ML. BOILING FLASK
BUTYL SEBACATE
3 WAY STOP COCK
RUBBER TUBING CONNECTION
3 WAY STOP COCK
3/8" COPPER TUBING
SALT WATER CELL
WATER CELL
SAMPLE
PURE WATER
RUBBER TUBING TO VACUUM PUMP
GROUND § JOINT
VAPOR TRAP

Fig. 1--Vapor-pressure apparatus

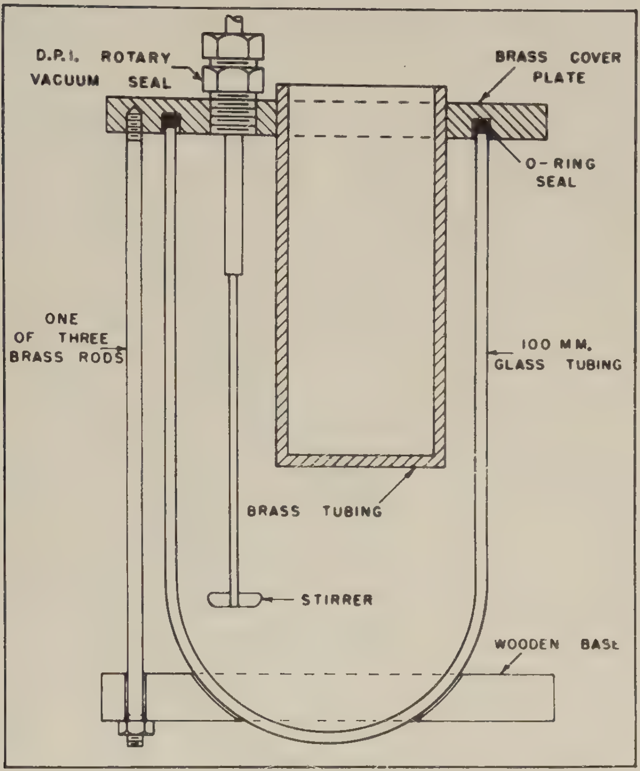

Fig. 2--Section view of test cell

sketch of the specially designed test cells is shown in Figure 2. Samples were degassed by successive sublimation in the test cells. Vapor pressure of a salt-solution sample in one cell was compared with the vapor pressure of pure water in the second cell by means of the differential manometer containing butyl sebacate. Manometer heights were read by means of a cathetometer. The test cells were accurately thermostated in a common bath. Short blasts of vapor from previously degassed water in the 300-ml boiling flasks were used to hasten the attainment of vapor-pressure equilibrium in the system when measurement was begun. For temperatures below 0° C (the freezing point of the pure water in the comparison flask), correction was made for the difference between the vapor pressures of ice and of super-cooled water.

Solution samples of varying concentration up to saturation (Cl ≈ 155 ⁰/oo) were obtained by evaporation of ordinary sea water at temperatures of about 80° C. Some precipitate ($CaCO_3$) appeared when the chlorinity exceeded 40 ⁰/oo and was followed by $CaSO_4 \cdot 2H_2O$ at concentrations above 70 ⁰/oo [THOMPSON and ROBINSON, 1932].

Samples for vapor-pressure measurement were decanted at room temperature. Concentration was determined by silver nitrate titration, and Higashi's values of density of concentrated sea-salt solutions were used in the calculation of chlorinity.

Several careful checks indicated that successive degassing of the sample did not cause sufficient loss of water to affect the concentration appreciably.

Experimental values of vapor-pressure lowering--The original experimental points are shown plotted in Figure 3 as vapor-pressure lowering (p_0 - p) versus reciprocal absolute temperature (1/T) for the various concentration samples used. Smooth curves were drawn through these points. A cross-plot (p_0 - p versus log chlorinity for various temperatures) was then made from the curves of Figure 3, and smooth curves were again drawn. Final curves of p_0 - p versus 1/T for various integral values of chlorinity were obtained by reading suitable values from the cross-plot and are shown in Figure 4. The smoothed numerical values used in plotting Figure 4 are given in Table 1.

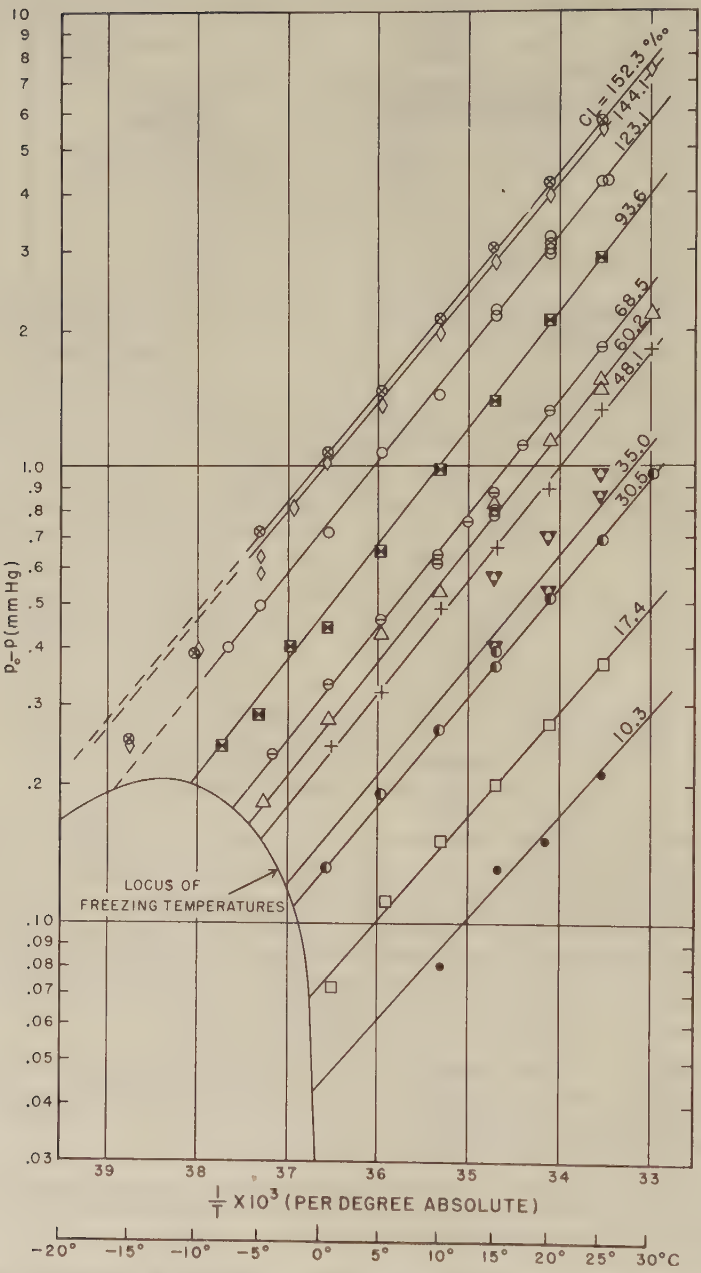

Fig. 3--Relationship of vapor-pressure lowering, $p_o - p$, for various sea-water solutions to reciprocal temperature (original experimental results)

Before the techniques of degassing and insuring pressure equilibrium in the system were perfected, runs on some of the early samples showed a very large scatter (as, for example, the Cl = 35 ^{o}/oo points in Fig. 3). All experimental points have been included in Figure 3 for the sake of completeness, but principal weight in smoothing and in determining the slopes of the curves has been given to the later, more reproducible measurements.

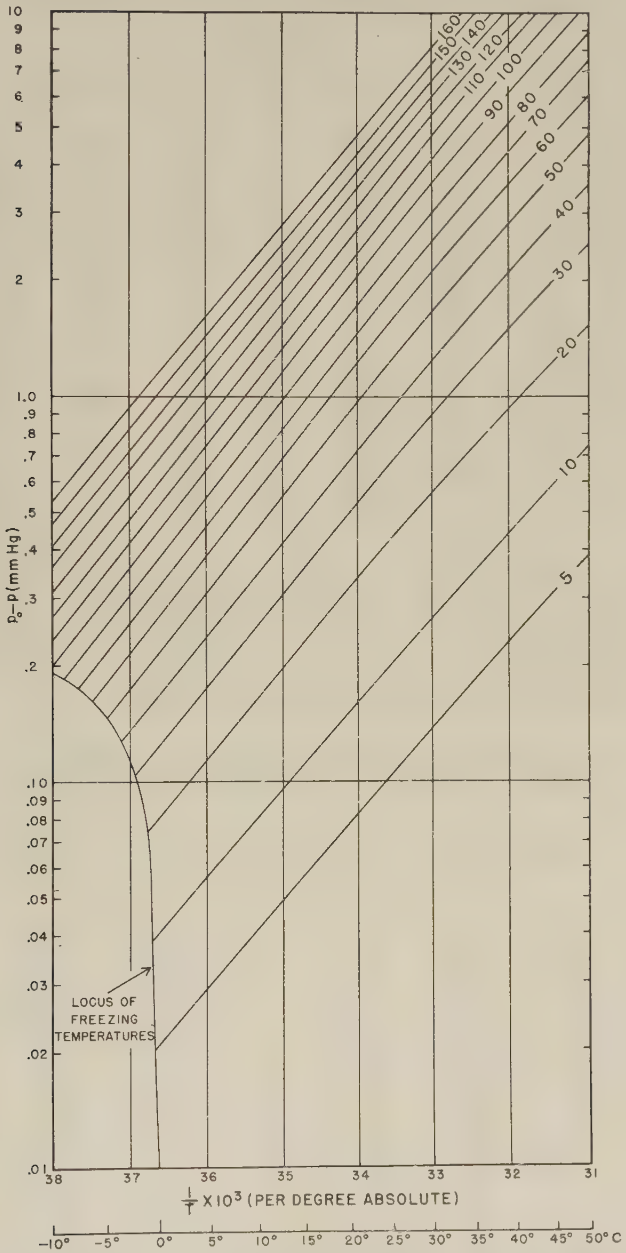

Fig. 4--Relationship of vapor-pressure lowering, $p_0 - p$, for various chlorinities to reciprocal temperature (smoothed original values)

Because of the inaccessibility of Higashi's vapor-pressure data in the original publication, it was deemed desirable to rework his data and tie them in with the results of this investigation, thus supplying a complete summary of vapor pressure of sea-salt solutions all the way from freezing to 175° C.

Table 1--Values of vapor-pressure lowering, in millimeters of mercury, used in Figure 4 (results of this investigation)

Chlorinity	Temperature °C									
	35	30	25	20	15	10	5	0	-5	-10
°/oo										
5	0.18	0.13	0.10	0.08	0.06	0.04	0.03	0.02	. . .	. . .
10	0.35	0.27	0.20	0.15	0.11	0.08	0.06	0.04	. . .	. . .
20	0.74	0.56	0.43	0.32	0.23	0.16	0.12	0.08	. . .	. . .
30	1.20	0.90	0.68	0.49	0.36	0.26	0.18	0.12	. . .	. . .
40	1.67	1.25	0.92	0.67	0.49	0.35	0.24	0.17	. . .	. . .
50	2.24	1.67	1.24	0.90	0.65	0.45	0.31	0.22	0.15	. . .
60	2.87	2.14	1.58	1.14	0.81	0.57	0.39	0.27	0.18	. . .
70	3.45	2.57	1.88	1.36	0.96	0.68	0.47	0.32	0.22	. . .
80	4.08	3.04	2.25	1.62	1.16	0.81	0.56	0.38	0.26	. . .
90	4.87	3.65	2.67	1.92	1.37	0.95	0.66	0.44	0.30	0.20
100	5.64	4.17	3.07	2.20	1.57	1.10	0.76	0.52	0.35	0.23
110	6.50	4.81	3.52	2.55	1.82	1.27	0.87	0.59	0.40	0.27
120	7.29	5.44	4.03	2.91	2.07	1.44	1.00	0.68	0.46	0.31
130	8.17	6.09	4.50	3.28	2.36	1.67	1.16	0.79	0.54	0.36
140	8.89	6.71	4.99	3.63	2.62	1.85	1.28	0.88	0.60	0.41
150	9.93	7.42	5.52	4.01	2.93	2.08	1.47	1.02	0.69	0.46
160	10.73	8.20	6.14	4.49	3.27	2.33	1.65	1.14	0.79	0.53

In re-examining Higashi's smoothed values and original experimental results, various large discrepancies were noted, and his 25°C measurements (which influenced the manner in which he drew his curves in the lower part of his temperature range) were found to show exceedingly large scatter. It was therefore decided to re-smooth Higashi's data, substituting our 25°C results for his. The data were plotted and cross-plotted in the same manner as that described above, and the final, smoothed curves for the entire temperature range from freezing to 175°C are shown in Figure 5. The values used to plot Figure 5 are given in Table 2.

Table 2--Values of vapor-pressure lowering, in millimeters of mercury, used in Figure 5 (re-smoothed results of Higashi)

Chlorinity	Temperature °C							
	175	150	125	100	75	50	25	0
°/oo								
10	33.0	18.5	9.7	4.75	1.99	0.74	0.20	0.04
20	72.6	41.0	21.1	10.2	4.40	1.54	0.43	0.08
30	118	65.8	34.0	16.4	7.08	2.50	0.68	0.12
40	168	94.5	49.3	23.9	9.99	3.58	0.92	0.17
50	227	128	66.5	32.1	13.2	4.75	1.24	0.22
60	298	168	86.2	41.0	16.6	5.96	1.58	0.27
70	374	213	108	52.0	21.1	7.41	1.88	0.32
80	457	257	132	62.2	25.1	8.85	2.25	0.38
90	551	308	157	74.7	30.1	10.3	2.67	0.44
100	640	363	184	87.4	34.8	11.7	3.07	0.52
110	749	425	217	103	41.1	13.6	3.52	0.59
120	868	486	248	117	46.3	15.2	4.03	0.68
130	1000	568	287	135	53.7	17.2	4.50	0.79
140	1115	630	317	151	58.4	18.8	4.99	0.88
150	1260	722	365	170	65.4	20.9	5.52	1.02
160	1440	822	408	188	72.8	22.8	6.14	1.14

WITTING [1908] gives a relation between vapor pressure and concentration of sea-salt solutions. This relation, based on thermodynamic equations and experimental freezing-point lowerings, should be valid for dilute solutions. The dashed curves in Figure 5 show Witting's equation to be in reasonably good agreement with our results at chlorinities of 10 and 20 °/oo.

In view of the smoothing processes used in obtaining the final values of vapor-pressure lowering, it is difficult to make an objective estimate of the accuracy of the results, but the authors feel this to be of the order of two per cent.

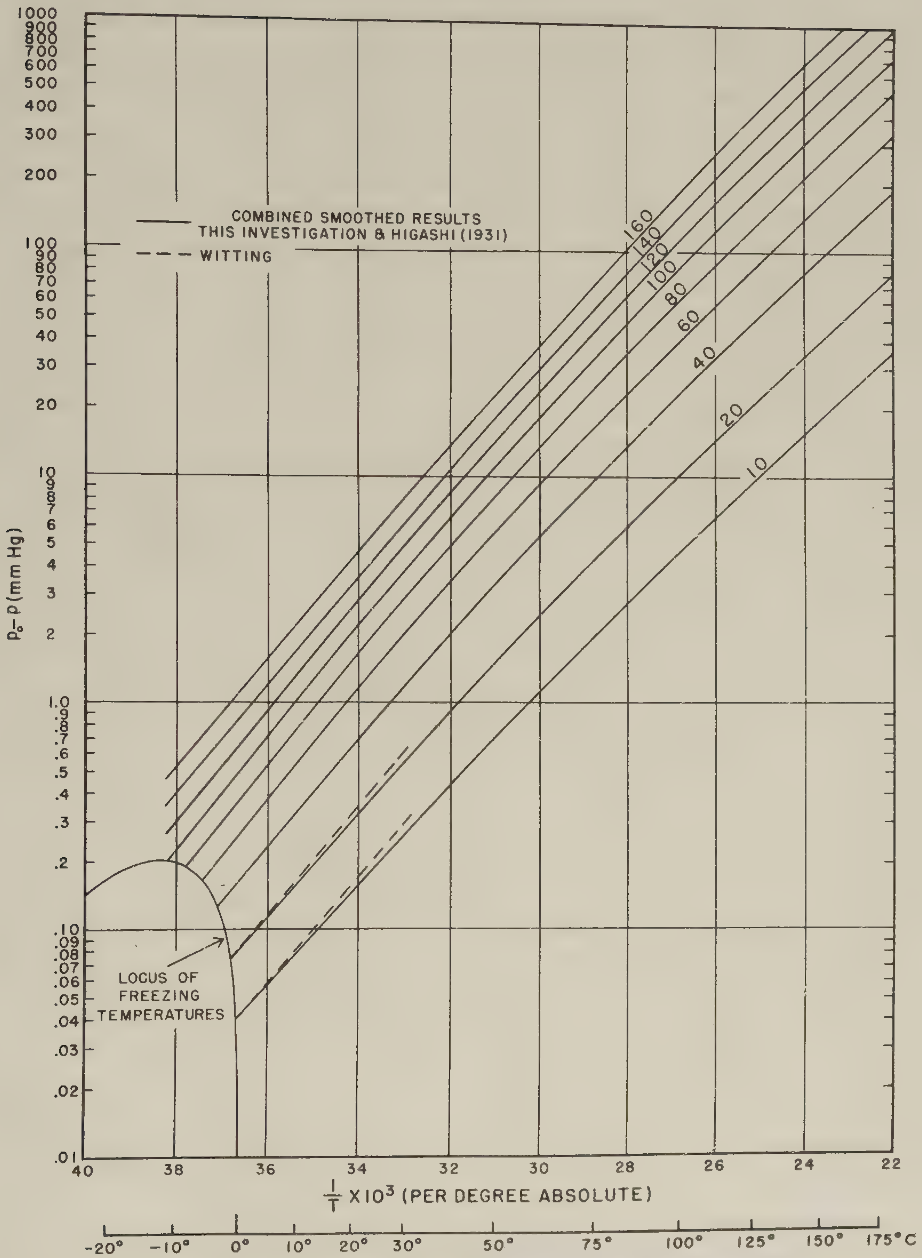

Fig. 5--Relationship of vapor-pressure lowering, $p_0 - p$, for various chlorinities to reciprocal temperature

Acknowledgment--The authors wish to thank Charles Keith and Alfred Woodcock for their continued interest and helpful advice on various experimental problems. The work was performed under a contract with the Office of Naval Research.

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Contribution No. 637

PHYSICAL OCEANOGRAPHY OF THE GRAND BANKS REGION AND THE LABRADOR SEA IN 1952[1]

By Floyd M. Soule, Senior Physical Oceanographer, U. S. Coast Guard

During 1952 the U. S. Coast Guard 180-foot tender-class cutter *Evergreen* served as oceanographic vessel of the ice patrol, as it has since 1948. The only major change affecting the oceanographic work, made since the 1951 season, was the lowering of the laboratory room temperature. This was accomplished by increasing the heat insulation of the bulkheads and deck and the installation of an air-conditioning unit. The rapid circulation of drier, cooler air has made possible better temperature control of the salinity bridge but has resulted in increased evaporation of salinity samples during the time their containers are open. The importance of this increased evaporation has not yet been determined.

The field work for the 1952 season began with the departure of the *Evergreen* from Argentia on the evening of 31 March for the first survey. The unusual absence of both berg and sea ice from the Grand Banks region obviated the necessity for surveying the area immediately adjacent to the more southerly steamer lanes and provided an opportunity for studying the waters farther to the north. The area immediately northward of the northeastern shoulder of the Grand Banks and Flemish Cap was free of sea ice, as was also the Bonavista triangle. If bergs subsequently moved south it would be useful to have a knowledge of the current system in this area. The Bonavista triangle is usually covered, at least in part, by sea ice until May. Very little information has been available regarding the northward flowing outer margins of the North Atlantic eddy north of Flemish Cap and no measurements had been made at this time of year. It was considered improbable that the Labrador shelf would remain free of sea ice across its complete width for the expected duration of the survey. The survey was planned, in the light of these considerations, to include the Bonavista triangle and a network of stations between it and Flemish Cap with the survey extended northward by a series of sections approximately normal to the coast and extending from the outer edge of the shelf to an eastern limit some 200 miles seaward of the continental slope.

The work of collection of data, encompassing 127 stations beginning with station 4614, began at the latitude of Flemish Cap on 1 April and

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EXTRACT FROM U. S. COAST GUARD BULLETIN NO. 38
Pages 31 to 100, Physical Oceanography of the Grand Banks Region and the Labrador Sea in 1952

was completed at about the 54th parallel on the early morning of 21 April. The *Evergreen* then returned to Argentia, arriving there on 23 April. During the survey it was necessary to heave to on account of weather twice, once for 13¼ hours on 12 to 13 April, and again for 14 hours on 17 to 18 April.

The *Evergreen* departed from Argentia on the afternoon of 28 April to begin the second survey. While the first survey covered many aspects of interest it could not also cover the early season current pattern in the area immediately east and south of the Grand Banks. The second survey was designed to get this, in addition to a small area of overlap with the first survey between 47° and 48° N., and to extend the surveyed area seaward far enough to delineate the outer boundary of Atlantic Current water in the sector southeastward of the Grand Banks. To accomplish this 100 stations were occupied, beginning with station 4741, between noon on 29 April and the morning of 12 May. The work of collection progressed from north toward south and was not interrupted by the weather. Upon conclusion of this work the *Evergreen* proceeded to 41°43′ N., 50°05′ W., where a carboy of surface water was collected for subsequent use as a substandard of salinity. The *Evergreen* then proceeded to Boston, arriving there on the evening of 15 May.

Toward the end of May the presence of some bergs in the Labrador Current just north of the Grand Banks made it seem desirable to get another current survey of the Grand Banks region. The *Evergreen* therefore returned to Argentia and departed there on the morning of 3 June to repeat the pattern of the second survey. The work of collection began at noon on 4 June with station 4841, and progressing from north toward south, was completed at station 4940 early on the afternoon of 16 June. It was not necessary to heave to on account of gales at any time during the survey, although the average speed was reduced by the high percentage (40 percent) of fog. Upon completion of the survey the *Evergreen* proceeded to Boston with arrival there on the evening of 19 June.

A postseason cruise was made to repeat the occupation of the Bonavista triangle and the section across the Labrador Sea from South Wolf Island, Labrador, to Cape Farewell, Greenland. This was accomplished with the occupation of 54 stations. The *Evergreen* departed from Boston on 7 July and from Argentia on 11 July and the work of collection of data at the triangle began on the evening of 12 July and was completed 3 days later. Work on the section across the Labrador Sea began on the early morning of 17 July and was concluded within the outer edge of a coastal belt of ice 12½ miles off Cape Farewell on the evening of 20 July. No gales were encountered. The *Evergreen* then proceeded via Argentia to Woods Hole where oceanographic equipment and personnel were discharged on the evening of 27 July to conclude the field work for 1952.

The oceanographic work was under the supervision of Oceanographer Floyd M. Soule United States Coast Guard who was assisted by Lt. Robertson P. Dinsmore, U. S. C. G., Lt. Rudolph E. Lenczyk, U. S. C. G. and Lt. Jay H. Bramson, U. S. C. G. Other assistants in the observational work were Francis N. Brown, yeoman second class; Lewis M. Lawday, aerographer's mate, second class; Donald M. McGill, aerographer's mate, third class; Hugh R. McCartney Jr., aerographer's mate, third class; and Joseph R. Stefanick, seaman, all United States Coast Guard.

Of the 381 stations occupied during the season and postseason cruises, the 24 stations comprising the section across the Labrador Sea were occupied from the surface to as near bottom as was practicable, and at the remaining 357 stations the observations extended to a depth of about 1,500 meters where the depth of water permitted. As in previous years the intended depths of observation, in meters, were 0, 25, 50, 75, 100, 150, 200, 300, 400, 600, 800, 1,000, and thence by 500-meter intervals. For the first survey, the dynamic topography of the southern shallower part has been referred to the 1000-decibar surface and the northern deeper part has been referred to the 1500-decibar surface. The results have been presented in two charts having sufficient overlap to provide continuity in their interpretation. The 1,500-decibar surface has been used for reference in the section across the Labrador Sea. For all other stations the dynamic heights have been referred to the 1,000-decibar surface.

In addition to the usual measurements of temperature and salinity, 696 samples during the second cruise, and 288 samples during the postseason cruise, were taken for ultimate determination of total phosphorus concentration.

Temperatures were measured with deep sea reversing thermometers. Most of the protected thermometers were of Richter and Wiese manfacture but a small percentage were manufactured by Negretti and Zambra, G. M. Manufacturing Co., and the Kahl Scientific Instrument Corp. The depths of observation were based on Richter and Wiese unprotected thermometers. The thermometers were used in pairs. The thermometers were shifted periodically so that a thermometer eventually was paired with several other thermometers thus providing rather extensive intercomparison. This program permitted recognition of those thermometers which were not functioning properly and also permitted a determination of consistent errors in the scale correction in use. The series of intercomparisons provided means of estimating the precision of the temperature measurements. Considering 2,458 comparisons the probable difference between the corrected readings of a pair of thermometers was ±0.012° C. As many of the thermometers had recent laboratory comparisons with thermometers tested by the National Bureau of Standards, and as in most cases the temperatures are the means of the corrected readings of a pair of thermometers, it is considered that the observed temperatures listed in the table of oceanographic data have a probable error of ±0.01° C.

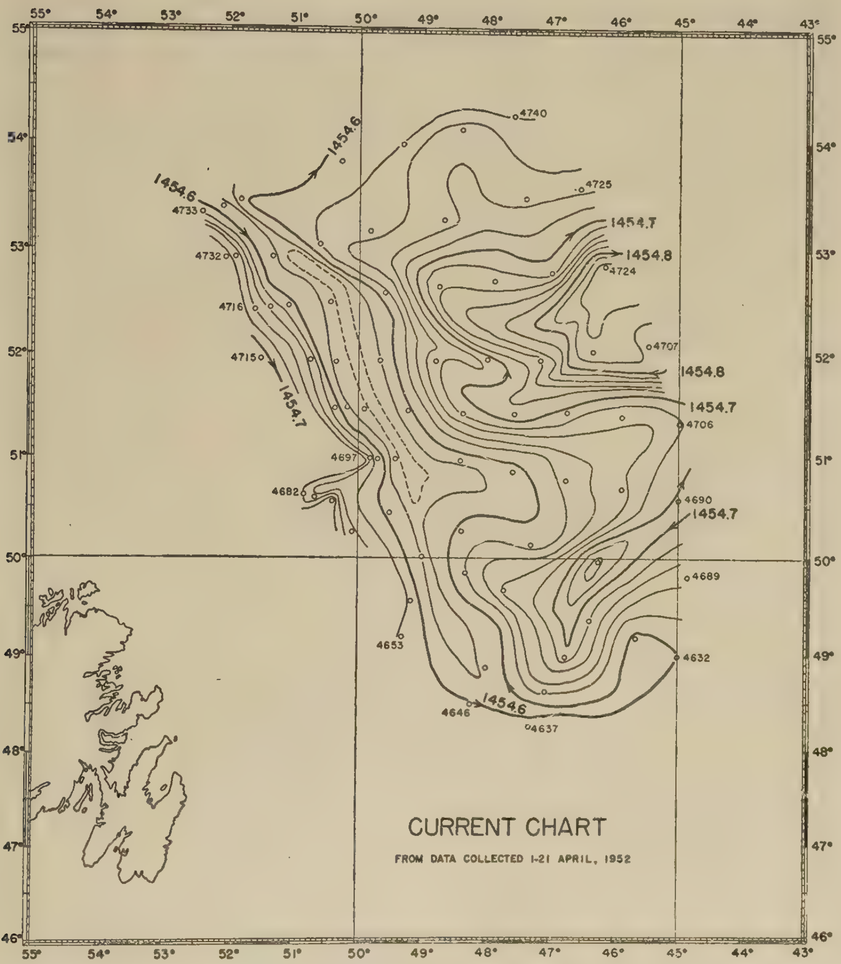
Salinities were determined, as in previous years, with a Wenner salinity bridge. Standardizations were made with water from an oil-sealed carboy of sea water. At least twice during each salinity run a sample of Copenhagen standard water of the batch P18 was measured as an unknown. At the end of each survey these measurements of standard water were used to correct all salinities determined during the survey. Indicated corrections thus obtained were less than 0.005°/₀₀ for the three surveys made during the season and so no correction was made. The salinities determined during the postseason cruise were corrected to Copenhagen water for each run. The precision of the salinity bridge measurements was about ±0.005°/₀₀. Since the calibration curve of the bridge was determined by silver nitrate titration, however, the accuracy of the salinities is no better than that of the latter method. As all samples from any one station were measured in the same salinity run any errors of standardization should not affect differences in salinity from level to level at a given station. Thus any cases of apparent instability arising from differences in salinity of more than 0.01°/₀₀ are considered to be real. It is of interest to note that several such cases of slight instability were found in 1952 in the intermediate water of the Labrador Sea. This water has usually been found to be of slight or indifferent stability.

The dynamic topography found during the first survey has been shown on two charts: figure 7 in which the heights of the sea surface have been referred to the 1,500-decibar surface and which covers the northern part of the surveyed area; and figure 8 in which the heights of the sea surface have been referred to the 1,000-decibar surface and which covers the southern part of the surveyed area. For the sake of continuity there is an area in which the two charts overlap. The 1,000-decibar surface, which is adequate for the Grand Banks region and preferable in view of the large proportion of shallow water stations there, is not deep enough for the Labrador Sea where the 1,500-decibar surface more nearly approximates the surface of no motion.

The area shown in figure 7 has infrequently been surveyed in summer and has never before been surveyed in April. There is, then, no basis for comparison to judge whether or not the current pattern found is unusual. That the seaward margin of the Labrador Current is found near the continental slope is to be expected from summertime observations. The northern limits of the North Atlantic eddy are inferred to have been located at about 55° N., and therefore are approximately in the same latitude found in summer. It was a surprise to find such large gradients in dynamic height as are shown in the western margins of the northward moving water. As indicated by figure 7, the water of most pronounced Atlantic characteristics was found at station 4724 where the salinities reached values above 35°/₀₀ with a maximum of

35.15. The meanders which have been found to characterize the outer margin of the North Atlatic eddy in the Grand Banks region are also present, at least as far north as 53° N., in figure 7.

Reference to figure 8 indicates that practically none of the Labrador Current was following the western branch along the Avalon Peninsula. Nearly all of the eastern branch appears to have been diverted northward without getting south of the latitude of Flemish Cap.



55°
54°
53°
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44°
43°
1454.6
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4716
4707
4715
1454.8
1454.7
1454.7
4706
4697
4682
4690
1454.7
4689
4653
4632
4646
1454.6
4637
CURRENT CHART
FROM DATA COLLECTED 1-21 APRIL, 1952

Figure 7.—Dynamic topography of the sea surface relative to the 1,500-decibar surface in the northern part of the area covered by the first survey, 1 to 21 April 1952. Oceanographic station positions are indicated and the station numbers given at turning points.

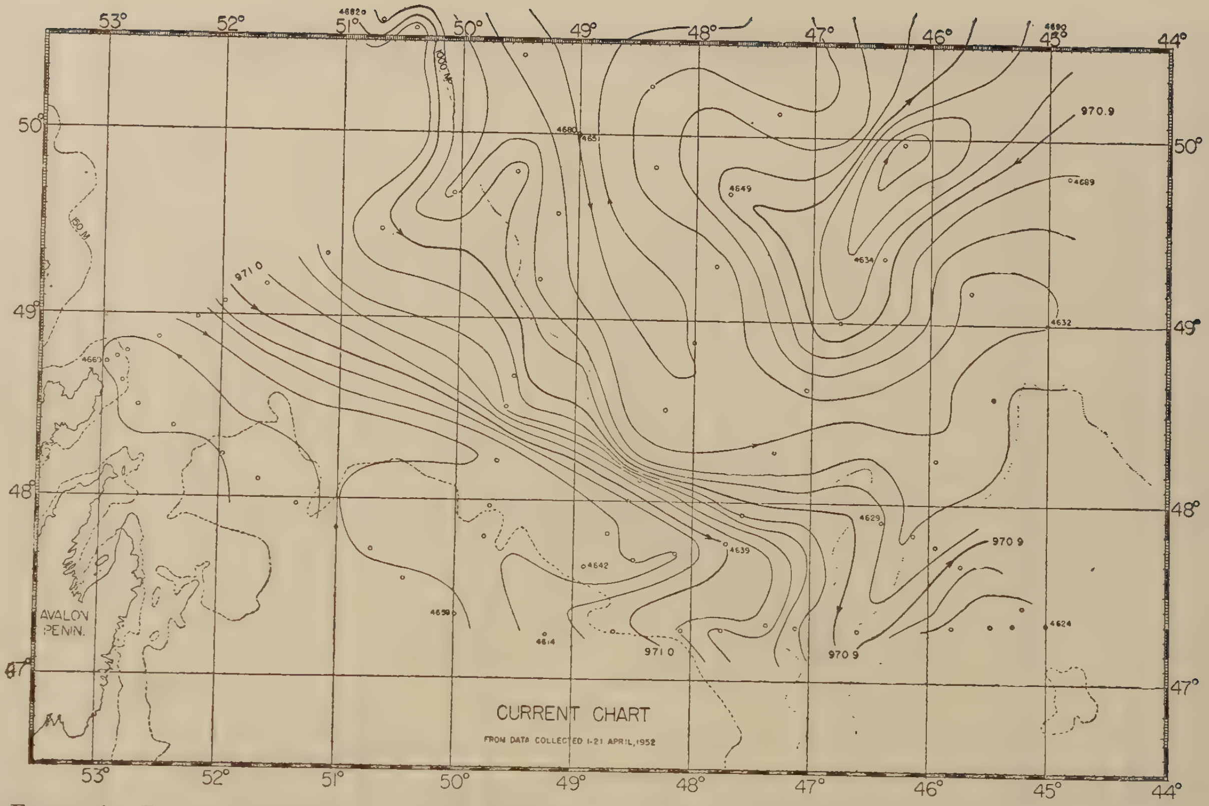

CURRENT CHART
FROM DATA COLLECTED 1-21 APRIL, 1952
AVALON PENIN.
150 M
1000 M
970.9
971.0
970.9
971.0
970.9
4682
4680
4651
4649
4634
4689
4690
4632
4669
4629
4639
4642
4624
4659
4614
53°
52°
51°
50°
49°
48°
47°
46°
45°
44°
50°
49°
48°
47°

Figure 8.—Dynamic topography of the sea surface relative to the 1,000-decibar surface in the southern part of the area covered by the first survey, 1 to 21 April 1952. Oceanographic station positions are indicated and the station numbers given at turning points.

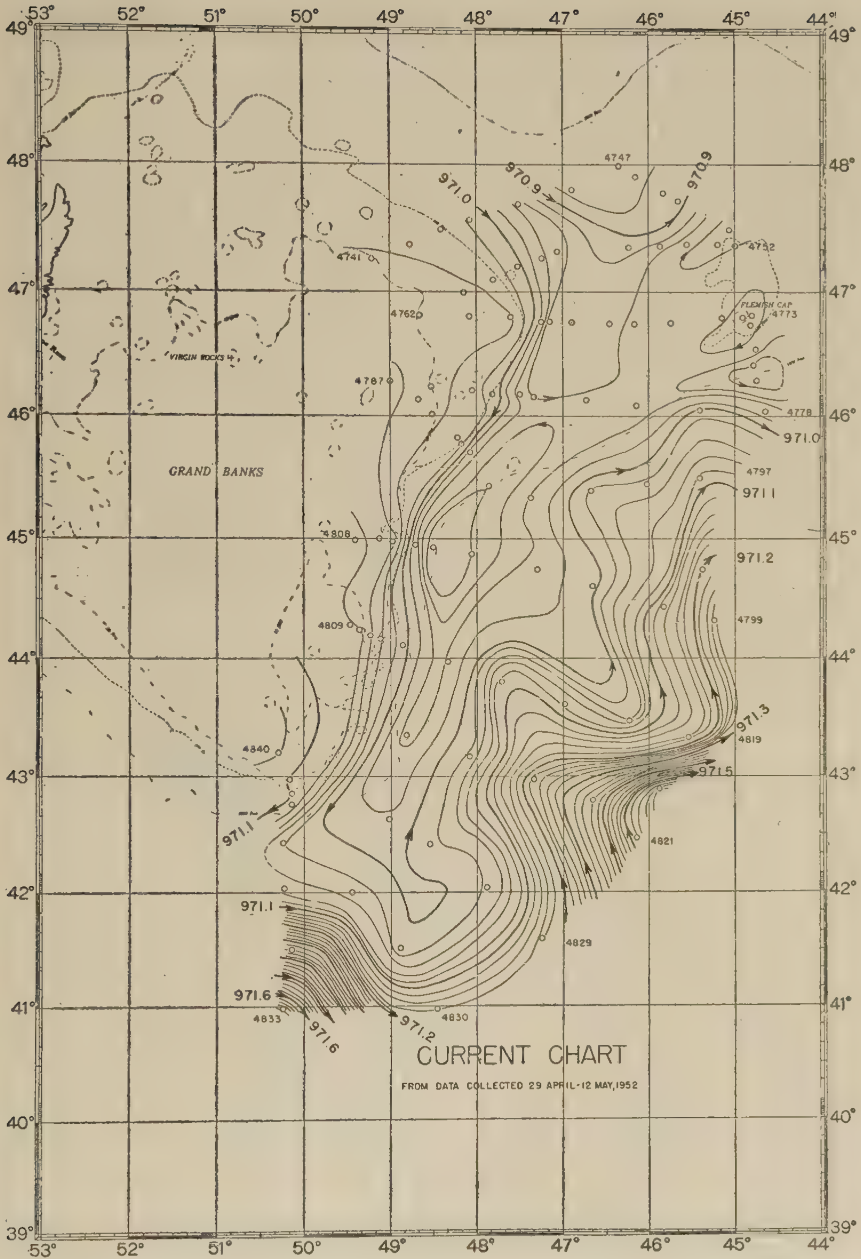
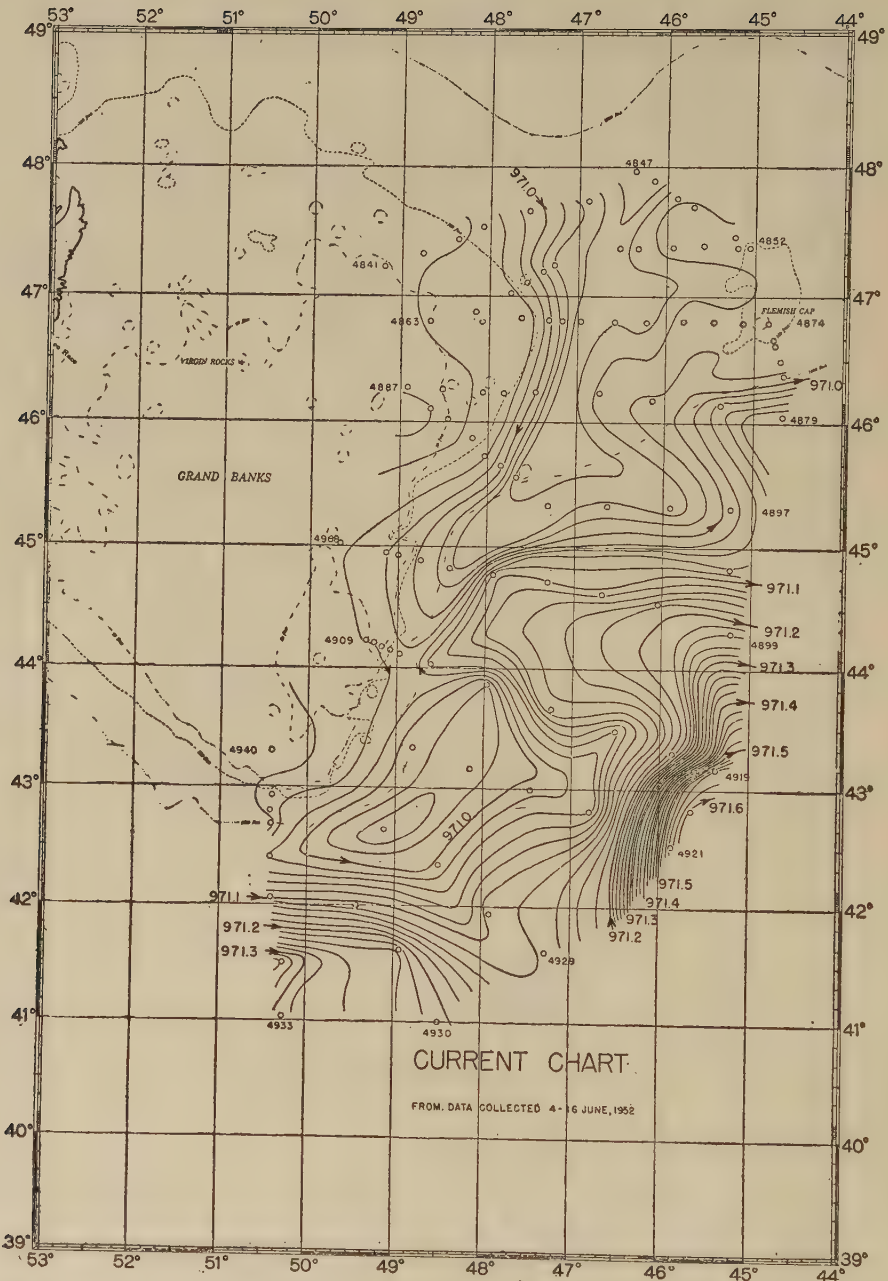

53°
52°
51°
50°
49°
48°
47°
46°
45°
44°
49°
48°
47°
46°
45°
44°
43°
42°
41°
40°
39°
GRAND BANKS
VIRGIN ROCKS
FLEMISH CAP
4747
4752
4773
4741
4762
4787
4778
4797
4799
4808
4809
4819
4821
4829
4830
4833
4840
971.0
970.9
970.9
971.0
971.1
971.2
971.3
971.5
971.1
971.1
971.6
971.6
971.2
CURRENT CHART
FROM DATA COLLECTED 29 APRIL-12 MAY,1952

FIGURE 9.—Dynamic topography of the sea surface relative to the 1,000-decibar surface from data collected 29 April to 12 May 1952. Oceanographic station positions are indicated and the station numbers given at turning points.


53°
52°
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48°
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46°
45°
44°
43°
42°
41°
40°
39°
GRAND BANKS
VIRGIN ROCKS
FLEMISH CAP
4847
4852
4874
4841
4863
4887
4879
4897
4968
4909
4899
4940
4919
4921
4929
4933
4930
971.0
971.1
971.2
971.3
971.4
971.5
971.6
CURRENT CHART
FROM. DATA COLLECTED 4-16 JUNE, 1952

FIGURE 10.—Dynamic topography of the sea surface relative to the 1,000-decibar surface from data collected 4 to 16 June 1952. Oceanographic station positions are indicated and the station numbers given at turning points.

Figures 9 and 10 show the dynamic topography of the sea surface relative to the 1,000-decibar surface found during the second and third surveys. The area covered in each of these surveys was the same and has a small area between 47° and 48° N., in which it overlaps that covered by the first survey. While the period covered by the observations of the second cruise (14 days) is somewhat longer than normal for a current survey of the Grand Banks, adjacent sections were as nearly synoptic as is ordinarily the case. The area of overlap shows little change between the first and second surveys. Not only were the surface velocities of the Labrador Current subnormal but in the valley between the Grand Banks and Flemish Cap the Labrador Current was especially weak at depths greater than about 400 meters. The dynamic topography is remarkably flat between 46° and 47° N., from the eastern edge of the Labrador Current eastward to Flemish Cap. Had bergs been present to enter the surveyed area via the Labrador Current from the north, the circumstances were such that if they arrived at the 47th parallel coincident with strong westerly winds they might have crossed this area of weak steady currents to get into positions of hazard near the 46th parallel in and east of the longitude of Flemish Cap. While the Labrador Current was weak it was possible for bergs to reach the Tail of the Banks. From this position there would have been little likelihood of them getting farther west than about the 51st meridian, and the locality in which they might have penetrated farthest into the steamer lanes was the relatively cold mixed water pool which extended southeastward nearly to 41° N., between 48° and 49° W.

Comparison of figure 10 with figure 9 shows the changes which took place during the 5-week interval between the second and third surveys. North of 45°30′ N., and west of 47° W., there was little change in the pattern and the principal change here was an increase of about 20 percent in the surface speed. East of 47° W., the area of very quiet water was replaced by a more active movement of mixed water returning northward. South of 45°30′ N., the most striking feature was the westward incursion of the salient associated with the Atlantic Current, and the recurving of practically all of the Labrador Current north of the 44th parallel. This left the colder mixed water southeastward of the Tail of the Banks circulating in a closed eddy. It is to be noted that although the dynamic height of the highest point in the edge of the Atlantic Current, in the southeastern margin of the survey, was very nearly the same and in the same position in the third survey as in the second survey, the difference in height between 41° N., and 42° N., at 50° W., was materially less than that found during the second survey.

Considered as a progressing meander, the salient of Atlantic Current water showed a northward rate of progression during the interval between the second and third surveys of about the same order of magnitude as in the cases of other meanders which have been charted from time to time. It is, of course, difficult to make an accurate estimate of the distance moved but the rate of progression of this meander would seem to have been about 2 or 3 miles per day whereas others have usually moved about 4 miles per day in this part of the area.

The volume of flow, mean temperature and heat transport of the Labrador Current have been determined for each of 19 sections occupied during the 1952 season and postseason cruises. Some of these sections have been occupied in other years and in the case of three sections, T, U, and W, numerous occupations in earlier years have provided a rough approximation to seasonal normals. The locations of sections T, U, and W are as follows: Section T extends southeasterly from about 46°20′ N., 49°00′ W.; section U extends eastward from the Grand Banks at about the 45th parallel; and section W extends southward from the Grand Banks at about the 50th meridian. The tentative normal seasonal variations in the Labrador Current at these sections have been given in bulletin number 36 of this series. Although little is known of the seasonal variation in the Labrador Current off South Wolf Island, Labrador, this section has been occupied once during each of 15 summers between 1928 and 1952 and average values at this section have been used for comparison with the results obtained in 1952. An insufficient number of earlier occupations of the Bonavista triangle sections and sections F, G, and H, intermediate between the triangle and Flemish Cap, are available for derivation of even average values for these sections.

Values found in 1952 are summarized in table 1 in which they are compared with such normal values as are available. In this table, as well as in the following discussion the volume transport is given in millions of cubic meters per second, the mean temperature and minimum observed temperature are given in degrees centigrade, and the heat transport is given in millions of cubic meter degrees centigrade per second.

It will be noted that the volume of flow of the Labrador Current in the Grand Banks region was subnormal in both the second and third surveys with the largest anomaly occuring at section W. The partial recovery at section T between the second and third surveys was accompanied by a larger diversion of this water southward of that section. This diversion, accomplished by the salient of Atlantic Current water also showed up in the mean temperature in which the anomaly changed from negative to positive values. The minimum temperatures were not as cold as normal in either survey.

Northward of Flemish Cap there was an increase in volume of flow at section G between the first and second surveys and very little change between the second and third surveys. The volume transport across the northwest section of the Bonavista triangle showed a marked increase between the first cruise and the post-season cruise, although

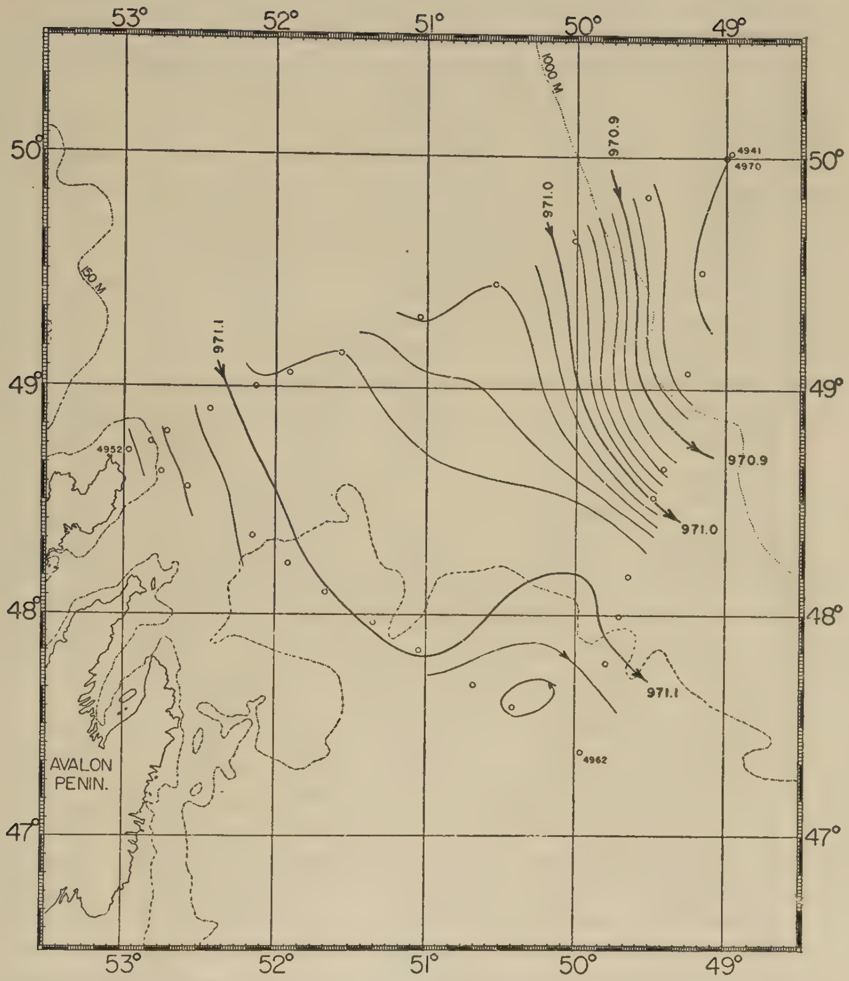
Table 1.—SUMMARY OF VELOCITY SECTIONS ACROSS LABRADOR CURRENT OCCUPIED IN 1952

Section	Volume transport			Mean temperature			Minimum observed temperature			Heat transport		
	1952	Normal	Anomaly	1952	Normal	Anomaly	1952	Normal	Anomaly	1952	Normal	Anomaly
First survey:												
NW	2. 77			0. 78			−1. 73			2. 16		
SW	0. 20 (NE.)			−1. 34			−1. 52			−0. 26 (NE.)		
SE	3. 56			1. 42			−1. 20			5. 08		
H	3. 32			1. 09			−1. 13			3. 63		
G	0. 79			1. 02			−0. 96			0. 81		
Second survey:												
G	1. 97			1. 20			−1. 02			2. 36		
F	2. 42			1. 93			−0. 94			4. 66		
T	1. 76	3. 43	−1. 67	1. 28	1. 83	−0. 55	−1. 11	−1. 36	+0. 25	2. 25	6. 28	−4. 03
U	4. 40	4. 63	−0. 23	1. 73	2. 08	−0. 35	−0. 74	−1. 16	+0. 42	7. 61	9. 63	−2. 02
W	1. 38	4. 12	−2. 74	1. 06	2. 95	−1. 89	−0. 43	−0. 50	+0. 07	1. 46	12. 15	−10. 69
Third survey:												
G	1. 89			2. 12			−1. 39			4. 01		
F	2. 19			2. 00			−0. 99			4. 38		
T	2. 47	2. 68	−0. 21	2. 01	1. 83	+0. 18	−1. 48	−1. 55	+0. 07	4. 98	4. 90	+0. 08
U	1. 90	3. 53	−1. 63	4. 97	2. 23	+2. 74	−1. 04	−1. 22	+0. 18	9. 43	7. 87	+1. 56
W	0. 45	4. 16	−3. 71	3. 47	3. 48	−0. 01	−0. 37	−0. 50	+0. 13	1. 56	14. 48	−12. 92
Postseason:												
NW	5. 31			0. 76			−1. 63			4. 03		
SW	0. 48			−1. 47			−1. 61			−0. 70		
SE	4. 36			1. 12			−1. 54			4. 90		
South Wolf Island	6. 37	4. 40	+1. 97	2. 63	2. 48	+0. 15	−1. 68			16. 76	11. 53	+5. 23

the mean temperature remained constant. At South Wolf Island the Labrador Current had a volume of flow nearly 50 percent greater than average, continuing the large values of volume transport which have been found there each year since and including 1949. The mean temperature at this section has been warmer than average and constant at 2.63° during each of the last 3 years. This would seem to give some weight to the speculation that more of the waters of the Labrador Sea recently have been brought into the closed circulation around its margins.

Considering the volumes of flow past the three sections of the Bonavista triangle, if there is no significant vertical motion across the reference surface the sum of the volume transports entering the triangle should equal the sum of the transports leaving the triangle. The figures for the April occupation showed a discrepancy of about a half-million cubic meters per second and it is presumed that some change occured during the period covered by the observations in spite of the good agreement between the two occupations of the station at the northeastern corner made at the beginning and end of the 3-day period of observations. The discrepancy was again about a half-million cubic meters per second for the figures obtained from the July occupation. In each case practically all of the current was following the eastern branch. For each occupation the dynamic topography at 100 decibars showed a pattern similar to that at the sea surface. Figure 11 shows the dynamic topography of the sea surface in the Bonavista triangle found during the postseason cruise.

In the Grand Banks region Labrador Current water and Atlantic Current water are present as water masses having characteristic temperature-salinity relationships. Usually, in addition, the mixed water formed from those water masses has a sufficiently uniform proportion of each to be considered as a virtual water mass. The T-S relationships found for these three water masses during the second and third surveys of 1952 have been examined and curves representing them are shown as solid lines in figure 12. The curves shown as broken lines give the relationships representing the means for the 8-year period 1934–41. The two sets of curves are of much the same shape for the Labrador Current water and the mixed water. There is a notable difference, however, between the 1952 conditions and the 8-year mean in the Atlantic Current water. Level for level the Atlantic Current water was lighter in 1952 than the mean, and the salinity minimum which occurs at a temperature of about 6° C in the mean curve was absent in 1952 and was only hinted at by a bulge occurring at a temperature of about 5° C. Although the 1952 curves for the mixed water and the Labrador Current water are similar in shape to the mean curves, the former at all levels and the latter at the deeper levels show lighter than mean densities because of decreases in salinity.


53°
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1000 M.
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4941
4970
50°
50°
150 M.
971.1
49°
49°
4952
970.9
971.0
48°
48°
971.1
AVALON
PENIN.
4962
47°
47°
53°
52°
51°
50°
49°

Figure 11.—Dynamic topography of the sea surface relative to the 1,000-decibar surface from data collected 12 to 15 July 1952. Oceanographic station positions are indicated and the station numbers are given at turning points.

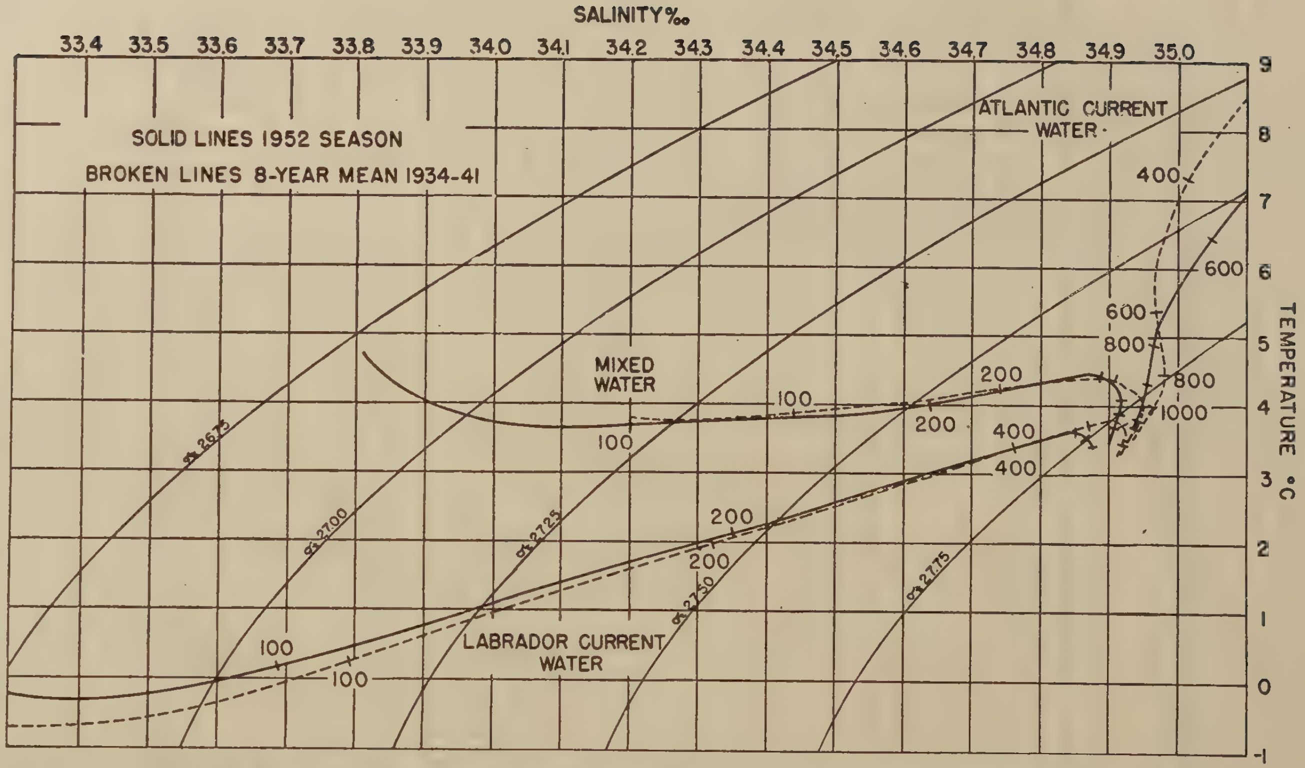


FIGURE 12.—Temperature—salinity relationships for Labrador Current water, Atlantic Current water, and mixed water found in the Grand Banks region. Solid lines show conditions during the 1952 season and broken lines represent the 8-year mean for the period 1934–41. An approximate depth scale in meters is given.

After the stations occupied during the second survey had been classified as to water mass, samples of water from a few stations selected as typical Labrador Current water and typical Atlantic Current water were analyzed for total phosphorus concentration by personnel of the Woods Hole Oceanographic Institution. If differences in total phosphorus can be used to trace water masses it would seem that these two water masses, having such widely different origins, might be expected to show characteristic differences if any exist. These preliminary measurements showed an encouraging difference. Since there was very little overlapping range of either temperature or salinity in the two water masses, the concentration of total phosphorus was plotted against σ_t. Whereas the Labrador Current water all had about the same concentration of total phosphorus, in the Atlantic Current water samples measured the phosphorus had low values in the lighter water, increased to a maximum at intermediate densities and then decreased toward the steady concentration characteristic of the Labrador Current water. The preliminary results were sufficiently encouraging to warrant the analysis of additional samples collected. This work is now in progress and will be reported upon when complete.

The water of the North Atlantic eddy is characteristically warm and the Labrador Current water and the mixed water are colder. In crossing from the warm water to the cold water the transition is abrupt and at the sea surface the change is so striking that this steep horizontal temperature gradient has been called the "cold wall". The melting of ice will of course proceed at a greater rate in the warm water than in the cold water. The location of this transition zone is consequently of importance in determining the boundary of the area which is ice infested. If, as is the case, this transition zone is not stationary, the prediction of the location of the boundary of the ice infested area must embody the prediction of the location of the transition zone in depths of the order of magnitude of the draft of an iceberg. Its location at the sea surface may be different from its location a short distance below the surface and it can be delineated only by subsurface measurements. To eliminate the more rapid fluctuations at the surface the criterion of the boundary of North Atlantic Current water was taken as the condition that a temperature of 6° C corresponded to a salinity of 34.95°/oo.

In the vicinity of the Grand Banks this boundary is irregular in shape and to get a numerical measure of its general advance toward or retreat from the Grand Banks, the area between the boundary and certain fixed rhumb lines was used. These lines were the 45th parallel, the 49th meridian and a line from 43° N., 49° W., through 42° N., 47° W., extended to the boundary. This area was larger or smaller as the boundary retreated from or advanced toward the Grand Banks. It was assumed that the position of the boundary was determined by the relative strengths of the Labrador Current and the Atlantic Current. The relationship was adopted that the area would be increased by 10,000 square kilometers for each million cubic meters per second volume of flow of the Labrador Current entering the area past section U. After adjustment of the measured area by the subtraction of the appropriate area for the measured volume transport of the Labrador Current, the remaining adjusted area, A, was considered to represent the effects of causes associated with the North Atlantic eddy.

Assuming that changes in the strength of the North Atlantic eddy were proportional to changes in the difference in sea level between Bermuda and Charleston, S. C., the fluctuation of the value, sea level at Charleston minus the departure from average at Bermuda, was studied in relation to fluctuations in the adjusted area. If A is expressed in units of 10,000 square kilometers and H is the sea level at Charleston minus the Bermuda departure in feet 13½ months earlier, for 27 surveys made over the period 1934 to 1941 the adjusted area was given by the expression

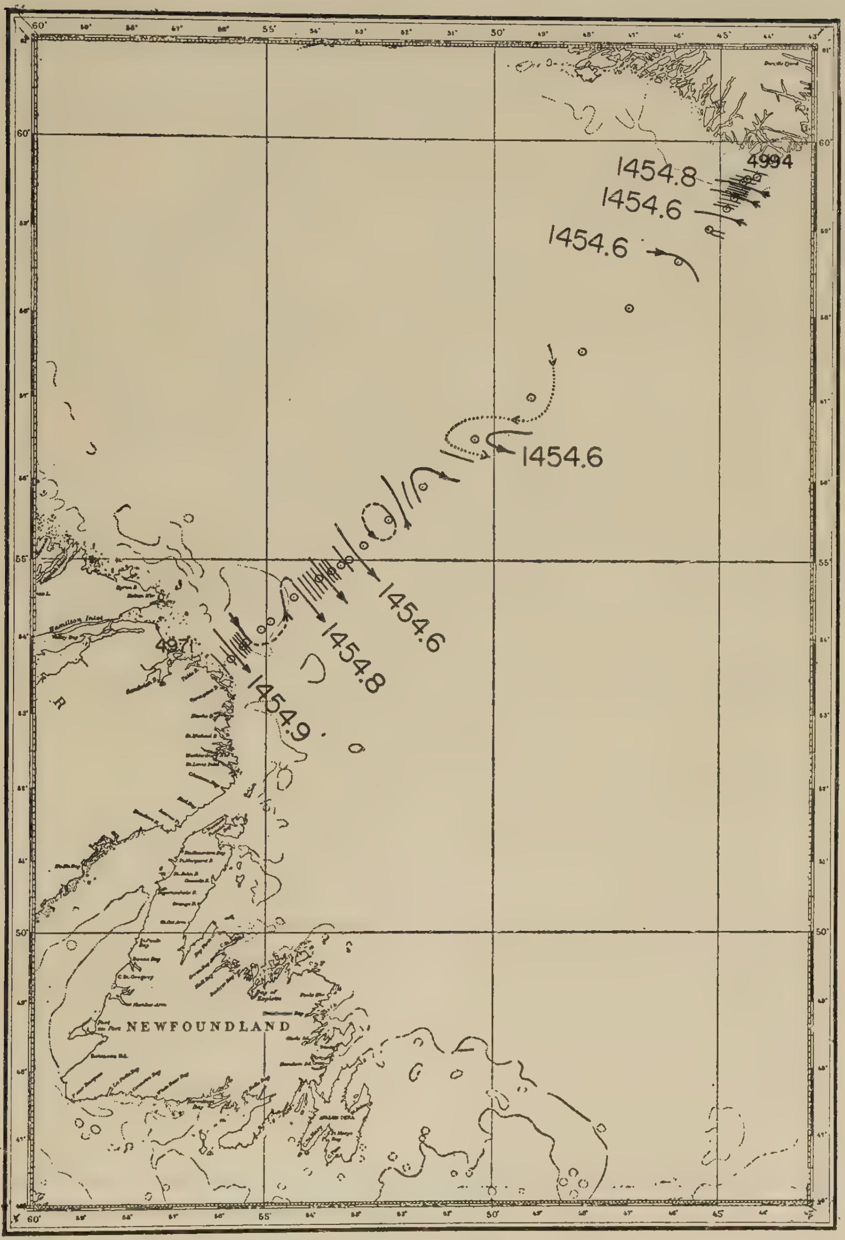
$$A=6.8(H-5.07)+1.34$$

Since the resumption of oceanographic work by the International Ice Patrol following World War II the following surveys have been made; one in 1948, two in 1949, three in 1950, two in 1951 and two in 1952. The above relationship could not be followed for these 10 postwar surveys, even approximately, until it was realized that instead of a phase difference of 13½ months, the postwar observations had a similar relationship but with a phase difference of 11½ months. Keeping these two different time lags, the combined 37 surveys give the relationship

$$A=6.97(H-5.07)+1.67$$

for computing the adjusted area with a probable error of $\pm 1.5\times 10^4$ square kilometers. No explanation is offered for the apparent change of 2 months in the time lag.

The dynamic topography of the sea surface deduced from the data collected during the occupation of the section across the Labrador Sea from South Wolf Island, Labrador, to Cape Farewell, Greenland, during the postseason cruise is shown in figure 13. Off South Wolf Island the Labrador Current is seen to have two bands separated by the shoal off Hamilton Inlet. Offshore of the major band over the continental slope there seems to be a closed cyclonic eddy. Seaward of this, at about 56° N., 52° W., the dynamic topography is interpreted as showing the extreme northwestern margins of the North Atlantic eddy as this northward flowing water curves to the eastward. Northward of this the outer margin of the North Atlantic eddy is


60°
55°
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1454.8
4994
1454.6
1454.6
1454.6
1454.6
1454.8
4971
1454.9
NEWFOUNDLAND

FIGURE 13.—Dynamic topography of the sea surface relative to the 1,500-decibar surface from data collected 17 to 20 July 1952. Oceanographic station positions are indicated and the station numbers are given at turning points.

joined by water which has recurved southward from the West Greenland Current. Northward of about 59° N., to the beach at Cape Farewell the West Greenland Current is shown. Since only a single section is available, the direction of flow is uncertain and the course of the dynamic isobaths shown in figure 13 has been deduced by drawing heavily upon what is known from earlier observations and upon the distribution of temperature and salinity.

Of the several bergs tracked by the ship occupying ocean station Bravo the only berg followed for several days was one first picked up at 56°15′ N., 51°25′ W., at 1600 on 10 April. The successive positions of this berg from 2000 on 10 April until 0630 on 21 April, when it had been reduced in size to a growler, have been plotted in the left half of figure 14. Plotted in the right half of this figure are the wind observations reduced to a series of vectors representing one-fortieth of the successive trajectories of an air particle starting from 56°14′ N., 51°20′ W., the position of the berg at 2000 on 10 April. The resultant trajectory is shown as a vector directed toward 204½°. Assuming that the wind current was directed 45° to the right of the wind and that the wind factor was 0.025 the resultant water movement has been plotted as directed toward 249½°. The resultant berg drift, obtained from the left half of figure 14, was directed toward 168½° and has been assumed to represent the resultant water movement composed of steady current and wind current components. The vector representing the water movement from steady currents, then, had a direction of 103½° and the average speed of the steady currents was 3¾ miles per day or about 0.16 knot.

The gaps in our knowledge are too large and numerous to permit us to draw definite conclusions from the above. We do not know the depth of the wind current with respect to the draft of the berg but it is assumed that in April the stability of the water column in this vicinity is slight. We do not know what seasonal variations in the steady current pattern take place between April and July but we assume they are small in this vicinity. The direction and speed of the steady currents deduced in the paragraph above are of the order of magnitude of those which can be found in figure 13 and it is considered probable that this berg (and the others found in the vicinity of ocean station Bravo) arrived at this locality from east of Cape Farewell (rather than from the Labrador side).

The temperature distribution along the section across the Labrador Sea from South Wolf Island, Labrador, to Cape Farewell, Greenland, found during the 1952 post-season cruise is shown in figure 15. The salinity distribution in the Greenland half of this section is given in figure 16. Referring to the temperature section, the frigid part of the Labrador Current is to be seen over the continental shelf and adjacent to it is the warmer part of the Labrador Current over the continental slope. The tongue of warm water, which usually extends from the

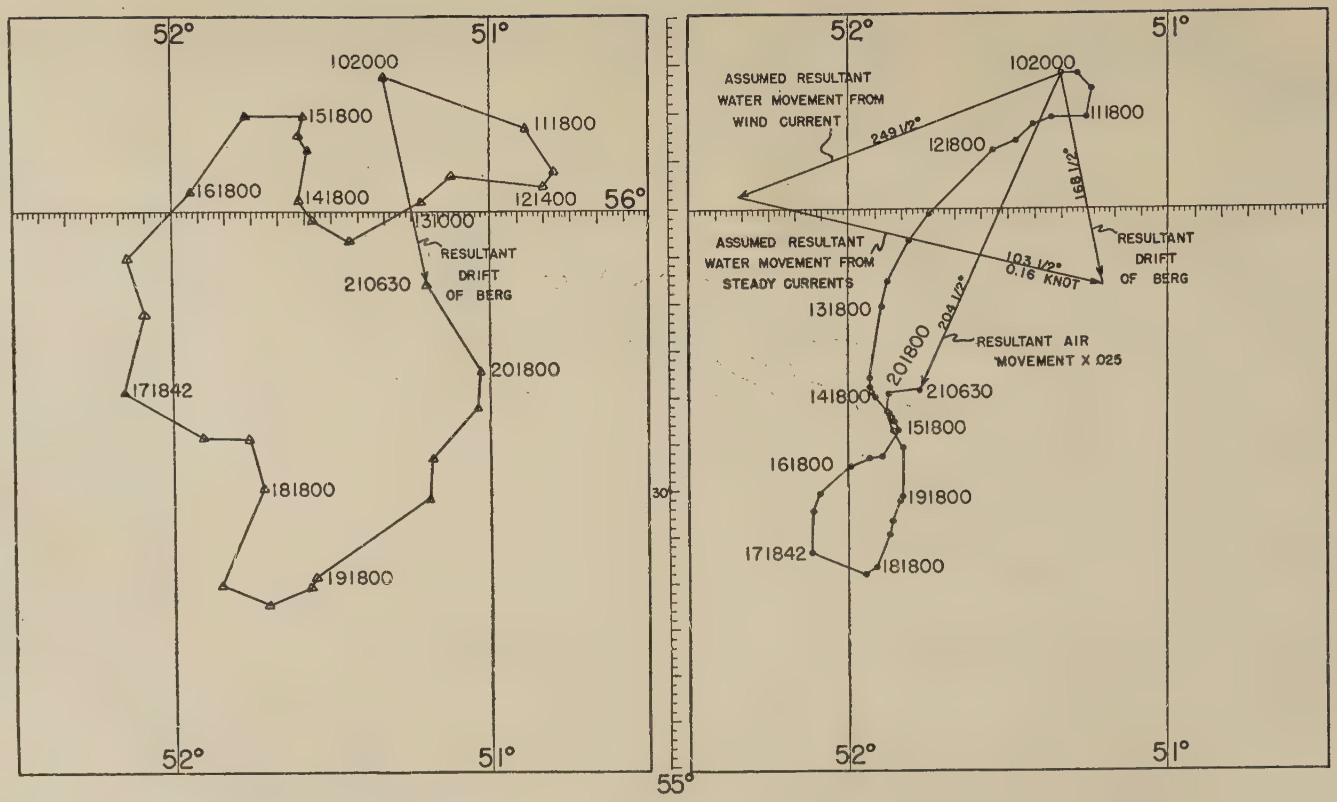
52°
51°
56°
55°
30
102000
111800
121400
131000
141800
151800
161800
171842
181800
191800
201800
210630
RESULTANT DRIFT OF BERG
121800
131800
ASSUMED RESULTANT WATER MOVEMENT FROM WIND CURRENT
ASSUMED RESULTANT WATER MOVEMENT FROM STEADY CURRENTS
RESULTANT AIR MOVEMENT X .025
249 1/2°
168 1/2°
103 1/2° 0.16 KNOT
204 1/2°

FIGURE 14.—Observed drift of berg 10 to 21 April 1952 and trajectory of air particle with magnitudes of vectors multiplied by 0.025.

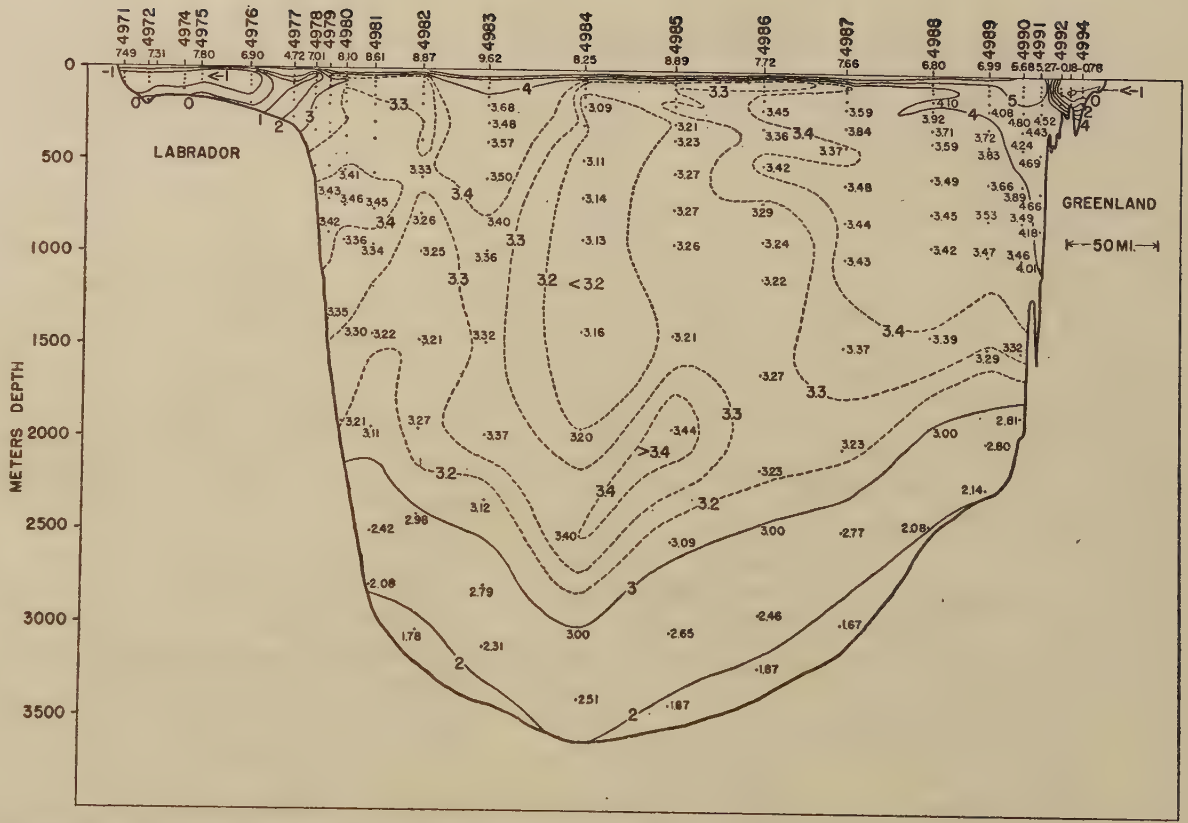

FIGURE 15.—Temperature distribution between South Wolf Island, Labrador, and Cape Farewell, Greenland, 17 to 20 July 1952.

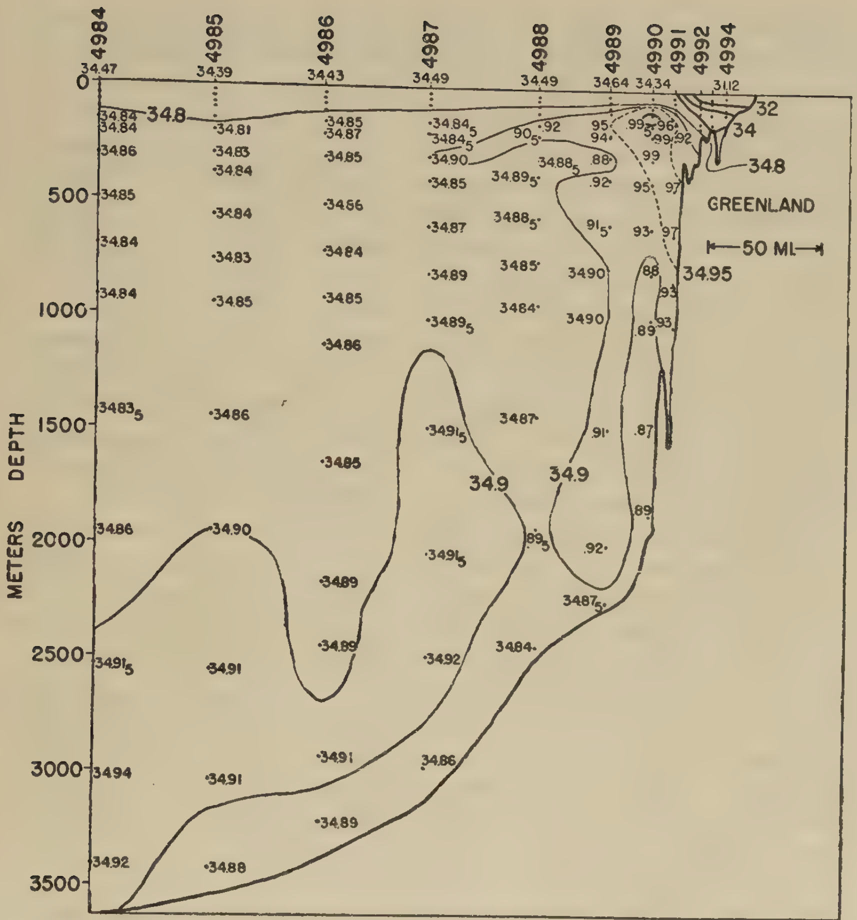

Figure 16.—Salinity distribution off Cape Farewell, Greenland, 18 to 20 July 1952.

surface just off-shore of the Labrador Current downward and westward to intersect bottom at intermediate depths on the continental slope, is shown reaching bottom at about 800 meters and associated with the warm water in the upper layers near station 4983. Defined by the 3.4° isotherm, this temperature maximum is interrupted by colder water at station 4982. The warm water at station 4983 is considered to be associated with the North Atlantic eddy and the cyclonic circulation about station 4982 probably brings some of this warmer water into the deeper circulation of the Labrador Current.

The temperature minimum in the intermediate water of the Labrador Sea was not as uniform in temperature as usual and while at stations 4985 and 4986, its temperature was about the same as found in 1951, the temperatures at station 4984 were about a tenth of a degree colder. The maximum temperatures below this temperature minimum are outlined by the 3.3° and 3.4° isotherms.

On the Greenland end of the section the cross-sectional areas in which the temperatures are higher than 4° and 5° show little change from the conditions found in 1951. Reference to figure 16, however, reveals a noticeable, though slight, increase in the values of maximum salinity. The salinity maximum, which was remarkably constant at about 35.04°/₀₀ during the 1930's dropped with the disappearance of the Irminger Current from this vicinity to 34.97 in 1949, 34.99 in 1950, 34.96 in 1951, and in 1952 was 35.01°/₀₀. This hints that the Irminger Current after an almost total absence of 4 years from the Cape Farewell area, may be on the point of returning to its former values. As has been pointed out in recent bulletins of this series, maximum salinities below the normal 35.04°/₀₀ but about 35.00°/₀₀ may be explained by postulating small direct contributions from the outer margins of the North Atlantic eddy in longitudes immediately eastward of Cape Farewell and not dependent upon the recurvature of the Irminger Current in the vicinity of Iceland.

Examination of the velocity profile of the West Greenland Current off Cape Farewell in the summer of 1952 shows a volume transport of 5.93 million cubic meters per second with a mean temperature of 3.79° C and a heat transport of 22.50 million cubic meter degrees centigrade per second. The corresponding normal values (derived in Bulletin No. 35 of this series) for this time of year are 4.51, 4.70, and 21.22 whence the volume of flow was 1.42 above normal, the mean temperature was 0.91 below normal with the heat transport 1.28 above normal. If the West Greenland Current is considered to be made up exclusively of an East Greenland Current component of constant mean temperature of 3.2 and an Irminger Current component of constant mean temperature 5.5, the observed West Greenland Current can be broken down into these components with volumes of flow of 4.40 and 1.53 respectively. As the seasonal normal values for these components are 1.56 and 2.95, the assumed constant mean temperatures lead to the conclusion that the volume of the East Greenland Current component was about three times its normal value and the Irminger Current component was about half its normal volume transport. If, however, the West Greenland Current at Cape Farewell was not made up exclusively of East Greenland Current and Irminger Current components, the contribution of the Irminger Current component would be smaller than this computed volume transport.

The circulation deduced from the computed values of volume transport, as described above and as given in table 1, is shown schematically in figure 17. In this figure the computed volumes have been rounded to the nearest 0.1 million cu.m/sec, and in the cases of the two occupations of the Bonavista triangle they have been adjusted so that the sum of the transports into the triangle equals the sum of the transports out of the triangle. In other words the

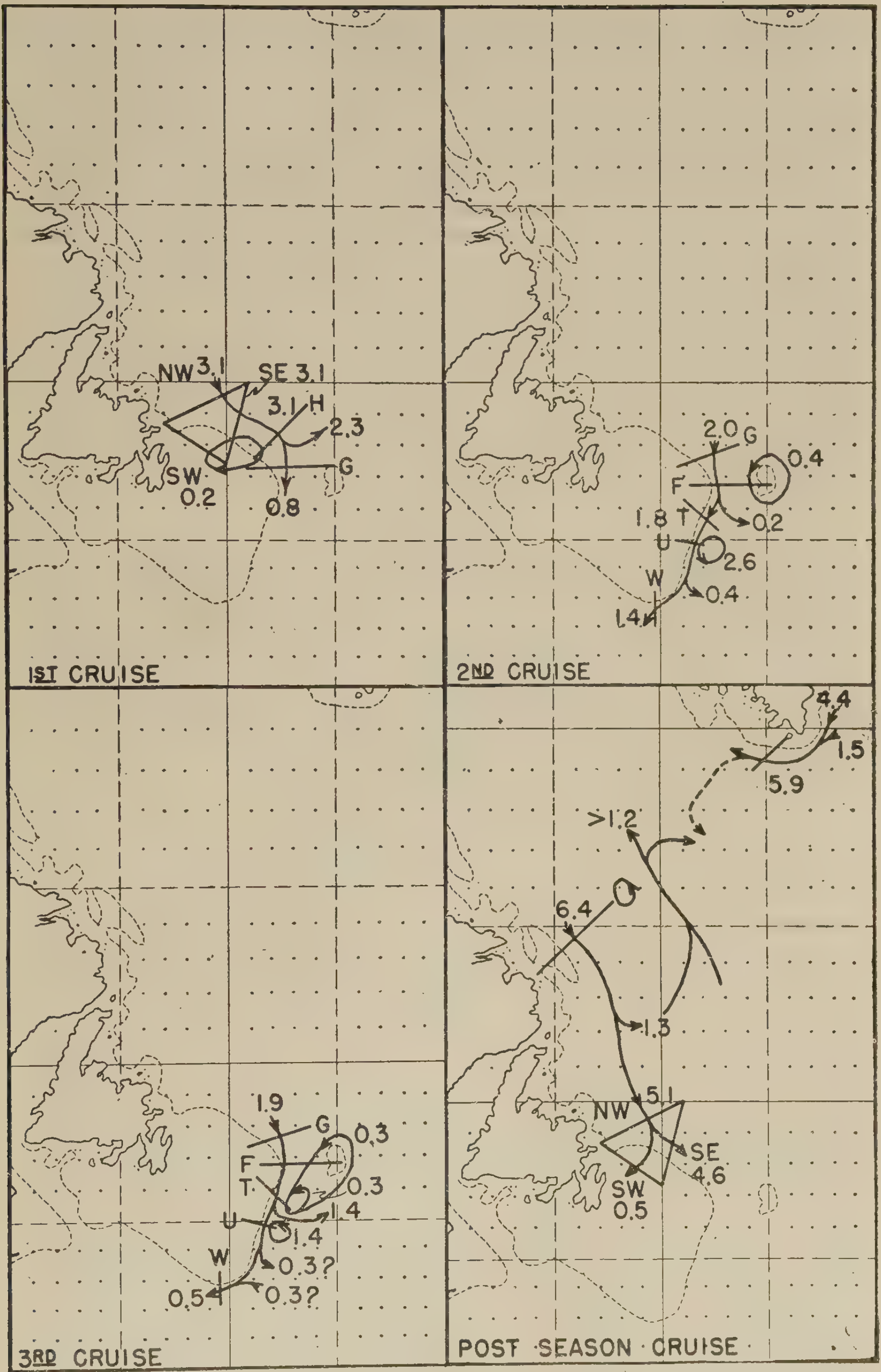
NW 3.1
SE 3.1
3.1 H
2.3
G
SW
0.2
0.8
1ST CRUISE
2.0 G
0.4
F
1.8 T
0.2
U
2.6
W
0.4
1.4
2ND CRUISE
1.9
G
0.3
F
T
0.3
1.4
U
1.4
W
0.3?
0.5
0.3?
3RD CRUISE
4.4
1.5
5.9
>1.2
6.4
1.3
5.1
NW
SE
4.6
SW
0.5
POST SEASON CRUISE

FIGURE 17.—Schematic representation of circulation deduced from sections occupied during 1952. Numerals indicate volume transport in units of cu.m/sec $\times 10^{-6}$.

vertical movement past the 1,000-decibar surface within the triangle has been considered to be negligibly small.

The dynamic height of the sea surface at South Wolf Island, Labrador, was somewhat higher than the dynamic height of the sea surface at Cape Farewell, Greenland (with reference to the 1,500-decibar surface in each case). This is not unusual and has been interpreted as the result of water entering the Baffin Bay-Labrador Sea system through the northern openings. Below a depth of about 200 meters, however, the water above the 1,500-decibar surface had a net northwesterly direction of flow, and for the entire section from South Wolf Island to Cape Farewell between the sea surface and the 1,500-decibar surface the net volume transport of 0.75 million cu.m/sec northwesterly was found. If there is a net transport through the northern openings into the Baffin Bay-Labrador Sea system, then the sinking past the 1,500-decibar surface must have exceeded these contributions by three-quarter million cu.m/sec.

SUMMARY

1. The surface circulation in the Grand Banks region and the adjacent area northward of the Grand Banks has been discussed on the basis of the dynamic topography found during three surveys made during the season. The exceptional absence of ice permitted, for the first time, the survey in April of the area from 47° N., to 54° N., between the Labrador Shelf and about 45° W. The season was characterized by a major recurvature of Labrador Current water northward, north of the latitude of Flemish Cap.

2. The circulation in the upper 1,000 meters in the Grand Banks region, with particular reference to the Labrador Current, has been given in greater detail on the basis of volume transport, mean temperature, minimum observed temperature and heat transport found during 18 occupations of 9 selected sections during the 1952 season. At three of these sections, for which the normal seasonal variation is available, the 1952 deficiency of the Labrador Current has been given.

3. The temperature-salinity relationships for the three water masses found in the Grand Banks region in 1952 have been compared with conditions found in other years.

4. The relationship between the location of the northern boundary of North Atlantic Current water in the Grand Banks region, the strength of the Labrador Current, and the difference in sea level between Bermuda and Charleston has been given further study with the results indicating that whereas the time lag between the Charleston-Bermuda section and the Grand Banks region was about 13½ months for the 27 surveys made during the period 1934–41, the lag was apparently 11½ months for the 10 surveys made during the period 1948–52.

5. The circulation in the southern part of the Labrador Sea has been inferred from examination of the dynamic heights along a section

from South Wolf Island, Labrador, to Cape Farewell, Greenland, the volume transport and mean temperature of the Labrador Current and West Greenland Current past this section, temperature distribution within the section and salinity distribution within the Greenland half of the section. The Irminger Current component of the West Greenland Current was still subnormal in 1952. Further examination of this section will be made on the basis of total phosphorus and reported upon in the next bulletin of this series.

The measurements of total phosphorus have not been completed and the results will be published in the next bulletin of this series. Except for phosphorus, the data collected during the 1952 season and postseason cruises are tabulated below. The individual station headings give the station number, date, geographical position, depth of water, and give the dynamic height of the sea surface used in the construction of the dynamic topographic charts shown in figures 7, 8, 9, 10, 11, and 13. The depths of water are rough approximations, being uncorrected sonic soundings based on a sounding velocity of 800 fathoms per second and containing an additional mechanical speed error of about ± 1/60. Where the depths of the scaled values are enclosed in parentheses, the data are based on extrapolated vertical distribution curves of temperature or salinity or both. Asterisks appearing before observed temperatures indicate that these temperatures were determined from the depth of reversal and the corrected reading of an unprotected thermometer. The symbol σ_t signifies 1,000 (density−1) at atmospheric pressure and temperature t.

Table of Oceanographic Data

STATIONS OCCUPIED IN 1952

Station 4614; Apr. 1; latitude 45°15′ N., longitude 49°13′ W.; depth 91 meters; dynamic height 971.027

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	−0.07	32.84	0	−0.07	32.84	26.39
25	−0.13	32.84	25	−0.13	32.84	26.40
51	−0.35	32.84	50	−0.35	32.84	26.40
76	−0.39	32.87	75	−0.40	32.87	26.43

Station 4615; Apr. 1; latitude 47°16′ N., longitude 48°39′ W.; depth 134 meters; dynamic height 971.010

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	−0.47	32.88	0	−0.47	32.88	26.44
25	−0.50	32.90	25	−0.50	32.90	26.45
49	−0.85	33.00	50	−0.85	33.00	26.55
74	−0.96	33.10	75	−0.95	33.10	26.63
98	−0.34	33.31	100	−0.30	33.31	26.77
123	−0.16	33.38				

Station 4616; Apr. 2; latitude 47°16.5′ N., longitude 48°05′ W.; depth 180 meters; dynamic height 970.976

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	−0.62	33.24	0	−0.62	33.24	26.73
24	−0.79	33.30	25	−0.80	33.30	26.78
48	−0.73	33.38	50	−0.75	33.39	26.86
72	−0.44	33.47	75	−0.40	33.49	26.93
95	−0.03	33.55	100	0.00	33.57	26.98
143	0.44	33.76	150	0.45	33.79	27.12

Station 4617; Apr. 2; latitute 47°17′ N., longitude 47°45′ W.; depth 227 meters; dynamic height 970.955

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	−0.53	33.25	0	−0.53	33.25	26.74
27	−0.56	33.41	25	−0.55	33.40	26.86
54	−0.17	33.56	50	−0.25	33.54	26.96
81	0.44	33.76	75	0.30	33.73	27.08
108	0.55	33.89	100	0.55	33.85	27.17
160	1.30	34.07	150	1.15	34.04	27.28
214	1.57	34.16	200	1.50	34.14	27.34

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4618; Apr. 2; latitude 47°19′ N., longitude 47°22′ W.; depth 357 meters; dynamic height 970.973

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	−0.46	33.35	0	−0.46	33.35	26.81
25	−0.45	33.35	25	−0.45	33.35	26.81
49	−0.41	33.44	50	−0.40	33.44	26.89
74	−0.26	33.50	75	−0.25	33.50	26.93
98	−0.13	33.56	100	−0.10	33.57	26.98
147	0.32	33.76	150	0.35	33.78	27.12
196	1.56	34.12	200	1.60	34.14	27.33
246	1.64	34.26	(300)	2.10	34.44	27.53

Station 4619; Apr. 2; latitude 47°17.5′ N., longitude 47°07′ W.; depth 1,090 meters; dynamic height 970.924

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	0.60	33.73	0	0.60	33.73	27.06
27	0.65	33.78	25	0.65	33.77	27.10
52	0.91	33.95	50	0.85	33.93	27.21
79	1.29	34.09	75	1.25	34.07	27.31
104	1.38	34.13	100	1.35	34.12	27.34
157	1.92	34.33	150	1.85	34.31	27.45
210	2.38	34.48	200	2.30	34.46	27.54
314	2.96	34.66	300	2.90	34.65	27.64
378	3.08	34.68	400	3.15	34.70	27.65
567	3.67	34.87	600	3.70	34.88	27.74
333	2.98	34.64	(800)	3.80	34.89	27.74
433	3.48	34.78	(1,000)	3.70	34.89	27.75

Station 4620; Apr. 2; latitude 47°17′ N., longitude 46°36′ W.; depth 596 meters; dynamic height 970.896

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.25	33.97	0	2.25	33.97	27.15
22	1.72	33.94	25	1.65	33.94	27.16
43	1.37	33.96	50	1.40	33.97	27.21
65	1.49	34.04	75	1.80	34.10	27.29
86	2.16	34.18	100	2.25	34.27	27.39
129	2.37	34.42	150	2.50	34.49	27.54
172	2.62	34.56	200	2.85	34.63	27.62
258	3.47	34.79	300	3.55	34.81	27.70
326	3.62	34.82	400	3.70	34.86	27.73
487	3.76	34.89				

Station 4621; Apr. 2; latitude 47°18.5′ N., longitude 45°49′ W., depth 290 meters; dynamic height 970.947

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.25	33.69	0	4.25	33.69	26.74
20	4.24	33.71	25	4.25	33.71	26.76
40	4.24	33.71	50	4.25	33.72	26.76
60	4.25	33.73	75	3.90	33.77	26.84
80	3.80	33.79	100	3.60	34.05	27.09
120	3.48	34.32	150	4.00	34.53	27.43
160	4.18	34.58	200	3.90	34.70	27.58
224	3.76	34.76				

Station 4622; Apr. 2; latitude 47°19′ N., longitude 45°29′ W., depth 258 meters; dynamic height 970.953

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.35	33.76	0	4.35	33.76	26.78
24	4.35	33.76	25	4.35	33.76	26.78
48	4.37	33.75	50	4.35	33.76	26.78
72	4.37	33.76	75	4.35	33.77	26.79
96	4.22	33.88	100	4.15	33.91	26.92
144	3.06	34.40	150	3.10	34.45	27.46
193	3.98	34.68	200	4.00	34.70	27.57
236	3.90	34.76				

Station 4623; Apr. 2; latitude 47°20′ N., longitude 45°18′ W., depth 220 meters; dynamic height 970.948

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.34	33.75	0	4.34	33.75	26.78
23	4.34	33.77	25	4.35	33.76	26.78
46	4.35	33.76	50	4.35	33.76	26.78
70	4.30	33.78	75	4.25	33.82	26.84
93	4.13	34.02	100	4.05	34.10	27.09
139	3.88	34.46	150	3.90	34.50	27.42
181	3.93	34.63	(200)	3.95	34.69	27.56

Station 4624; Apr. 2; latitude 47°20′ N., longitude 45°00′ W.; depth 181 meters; dynamic height 970.950

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.32	33.78	0	4.32	33.78	26.81
24	4.32	33.78	25	4.30	33.78	26.81
49	4.30	33.78	50	4.30	33.78	26.81
74	4.27	33.80	75	4.25	33.80	26.82
98	4.22	33.88	100	4.20	33.90	26.91
147	3.92	34.46	150	3.90	34.49	27.41

Station 4625; Apr. 2; latitude 47°25.5′ N., longitude 45°12′ W., depth 216 meters; dynamic height 970.945

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.38	33.74	0	4.38	33.74	26.77
27	4.40	33.74	25	4.40	33.74	26.77
53	4.38	33.76	50	4.40	33.76	26.78
80	4.30	33.82	75	4.30	33.80	26.82
106	4.14	34.04	100	4.20	33.97	26.97
159	3.86	34.48	150	3.85	34.42	27.36
212	3.92	34.66	200	3.90	34.63	27.52

Station 4626; Apr. 3; latitude 47°39′ N., longitude 45°44′ W., depth 286 meters; dynamic height 970.916

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.21	33.72	0	4.21	33.72	26.77
26	4.27	33.73	25	4.25	33.73	26.77
53	4.23	33.78	50	4.25	33.77	26.80
79	3.73	34.04	75	3.75	33.99	27.03
105	3.81	34.32	100	3.80	34.27	27.25
157	3.97	34.64	150	3.95	34.61	27.50
209	4.00	34.80	200	4.00	34.78	27.63
253	4.14	34.87				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4627; Apr. 3; latitude 47°45′ N., longitude 45°58′ W.; depth 444 meters; dynamic height 970.870

Observed values			Scaled values			
Depth, meters	Temperature ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	3.51	33.79	0	3.51	33.79	26.89
23	3.48	33.82	25	3.45	33.84	26.93
47	2.50	34.02	50	2.50	34.06	27.20
70	2.98	34.33	75	3.10	34.38	27.40
95	3.47	34.56	100	3.50	34.58	27.52
142	3.62	34.70	150	3.60	34.71	27.62
189	3.40	34.74	200	3.40	34.75	27.67
284	3.43	-----	300	3.50	34.85	27.74
378	3.82	34.89	(400)	3.85	34.90	27.74

Station 4628; Apr. 3; latitude 47°49′N.; longitude 46°08′ W; depth 1,006 meters; dynamic height 970.861

0	3.07	33.83	0	3.07	33.83	26.96
27	1.99	33.84	25	2.05	33.84	27.06
53	1.47	33.92	50	1.45	33.90	27.15
80	2.31	34.37	75	2.20	34.28	27.40
106	2.61	34.50	100	2.55	34.48	27.53
160	2.84	34.67	150	2.80	34.64	27.63
214	3.25	34.76	200	3.15	34.74	27.68
320	3.61	34.86	300	3.60	34.85	27.73
415	3.58	34.88	400	3.60	34.88	27.75
621	3.52	34.89	600	3.50	34.89	27.77
827	3.42	34.90	800	3.45	34.90	27.78
991	3.33	34.90	1,000	3.35	34.90	27.79

Station 4629; Apr. 3; latitude 47°53.5′ N., longitude 46°24′ W.; depth 1,162 meters; dynamic height 970.884

0	1.03	33.82	0	1.03	33.82	27.12
24	1.00	33.84	25	1.00	33.84	27.13
48	1.07	34.03	50	1.10	34.04	27.29
72	1.34	34.14	75	1.40	34.17	27.38
96	1.89	34.35	100	2.00	34.37	27.49
144	2.60	34.47	150	2.60	34.47	27.52
192	2.42	34.50	200	2.45	34.52	27.57
288	3.31	34.78	300	3.35	34.79	27.70
373	3.55	34.83	400	3.60	34.84	27.72
565	3.64	34.89	600	3.65	34.89	27.75
762	3.58	34.88	800	3.55	34.89	27.76
956	3.42	34.89	1,000	3.40	34.89	27.78
1,065	3.35	34.89				

Station 4630; Apr. 3; latitude 48°14′ N., longitude 45°57′ W.; depth 1,060 meters; dynamic height 970.847

0	2.74	34.10	0	2.74	34.10	27.21
27	2.20	34.27	25	2.20	34.25	27.38
53	3.07	34.49	50	3.00	34.48	27.49
80	3.24	34.52	75	3.20	34.52	27.51
106	3.29		100	3.30	34.55	27.52
160	3.07	34.68	150	3.10	34.66	27.63
213	3.46	34.78	200	3.40	34.76	27.68
319	3.63	34.85	300	3.65	34.84	27.71
393	3.63	34.88	400	3.60	34.88	27.75
584	3.53	34.88	600	3.50	34.88	27.76
782	3.46	34.88	800	3.45	34.88	27.76
983	3.33	34.90	1,000	3.35	34.90	27.79

Station 4631; Apr. 3; latitude 48°35′ N., longitude 45° 28′ W.; depth 1,005 meters; dynamic height 970.855

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	3.63	34.22	0	3.63	34.22	27.23
25	3.24	34.23	25	3.24	34.23	27.26
50	3.26	34.32	50	3.26	34.32	27.34
75	3.00	34.37	75	3.00	34.37	27.41
100	2.85	34.49	100	2.85	34.49	27.51
150	2.95	34.66	150	2.95	34.66	27.64
201	3.20	34.73	200	3.20	34.73	27.67
301	3.69	34.85	300	3.70	34.85	27.72
389	3.68	34.87	400	3.65	34.87	27.74
587	*3.59	34.89	600	3.60	34.89	27.76
789	3.50	34.89	800	3.50	34.89	27.77
962	3.32	34.89	(1,000)	3.30	34.89	27.79

Station 4632; Apr. 3; latitude 49°00′ N., longitude 45°00′ W.; depth 1,623 meters; dynamic height 970.840

0	3.33	34.42	0	3.33	34.42	27.41
24	3.29	34.43	25	3.30	34.43	27.42
49	3.15	34.44	50	3.15	34.44	27.44
74	3.18	34.45	75	3.20	34.45	27.45
99	3.08	34.56	100	3.10	34.56	27.55
147	3.58	34.79	150	3.55	34.80	27.69
197	3.58	34.83	200	3.60	34.83	27.71
296	3.59	34.86	300	3.60	34.86	27.74
403	3.49	34.86	400	3.50	34.86	27.75
604	3.55	34.88	600	3.55	34.88	27.75
804	3.40	34.88	800	3.40	34.88	27.77
1,010	3.34	34.88	1,000	3.35	34.88	27.77
1,520	3.27	34.93	1,500	3.30	34.93	27.82

Station 4633; Apr. 4; latitude 49°10′ N., longitude 45°40′ W.; depth 2,838 m.; dynamic height 970.834

0	3.93	34.40	0	3.93	34.40	27.34
25	3.86	34.40	25	3.86	34.40	27.35
50	3.40	34.45	50	3.40	34.45	27.43
75	3.15	34.47	75	3.15	34.47	27.47
100	2.94	34.53	100	2.94	34.53	27.53
150	3.02	34.67	150	3.02	34.67	27.64
200	3.35	34.78	200	3.35	34.78	27.69
300	3.18	34.83	300	3.18	34.83	27.75
411	3.29	34.85	400	3.30	34.85	27.76
610	3.26	34.87	600	3.25	34.87	27.78
806	3.39	34.88	800	3.30	34.88	27.78
1,007	3.37	34.89	1,000	3.40	34.89	27.78
1,512	3.27	34.91	1,500	3.30	34.91	27.81

Station 4634; Apr. 4, latitude 49°21′ N., longitude 46°24′ W.; dynamic height 970.907

0	5.10	34.21	0	5.10	34.21	27.06
24	5.10	34.22	25	5.10	34.22	27.07
49	4.87	34.25	50	4.85	34.25	27.12
73	4.72	34.34	75	4.70	34.34	27.20
98	4.52	34 37	100	4.50	34.37	27.26
147	3.18	34.43	150	3.20	34.44	27.44
196	4.12	34.74	200	4.15	34.74	27.58
294	3.63	34.79	300	3.65	34.79	27.67
392	3.86	34.88	400	3.85	34.88	27.72
584	3.58	34.89	600	3.55	34.89	27.76
773	3.54	34.89	800	3.50	34.89	27.77
970	3.46	34.88	1,000	3.45	34.89	27.77
1,470	3.33	34.88	1,500	3.35	34.88	27.77

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—*Continued*

Station 4635; Apr. 4; latitude 48°59.5′ N., longitude 46°46′ W.; depth 2,834 meters; dynamic height 970.919

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	5.26	34.21	0	5.26	34.21	27.04
22	5.23	34.21	25	5.20	34.21	27.05
44	5.16	34.21	50	5.15	34.21	27.05
66	5.13	34.22	75	5.00	34.33	27.16
87	4.85	34.44	100	4.85	34.50	27.32
131	4.89	34.58	150	4.65	34.60	27.42
175	4.35	34.63	200	4.40	34.69	27.51
262	4.57	34.86	300	4.20	34.86	27.68
315	4.05	34.86	400	4.00	34.88	27.71
491	3.95	34.90	600	3.80	34.90	27.75
678	3.68	34.90	800	3.60	34.90	27.77
857	3.56	34.895	1,000	3.50	34.89	27.77
1,321	3.32	34.88	(1,500)	3.30	34.88	27.78

Station 4636; Apr. 4; latitude 48°37.5′ N., longitude 47°03′ W.; depth 2,561 meters; dynamic height 970.848

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	4.31	34.36	0	4.31	34.36	27.27
25	4.02	34.36	25	4.02	34.36	27.30
50	3.19	34.45	50	3.19	34.45	27.45
75	2.90	34.50	75	2.90	34.50	27.52
99	2.77	34.51	100	2.80	34.51	27.53
150	2.99	34.68	150	3.00	34.68	27.65
200	3.54	34.80	200	3.55	34.80	27.69
299	3.35	34.82	300	3.35	34.82	27.73
355	3.41	34.84	400	3.45	34.85	27.74
535	3.47	34.86	600	3.45	34.87	27.76
719	3.46	34.88	800	3.45	34.88	27.76
913	3.43	34.88	1,000	3.40	34.88	27.77
1,420	3.34	34.87	(1,500)	3.35	34.87	27.77

Station 4637; Apr. 4; latitude 48°16.5′ N., longitude 47°19′ W.; depth 1,880 meters; dynamic height 970.842

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	2.34	34.32	0	2.34	34.32	27.42
26	2.21	34.36	25	2.20	34.36	27.47
52	2.35	34.43	50	2.35	34.43	27.50
78	2.40		75	2.40	34.44	27.51
104	2.36	34.44	100	2.35	34.44	27.51
156	2.91	34.64	150	2.85	34.62	27.62
208	3.31	34.78	200	3.25	34.77	27.70
312	3.51	34.82	300	3.50	34.82	27.72
415	3.52	34.86	400	3.55	34.86	27.74
626	3.66	34.90	600	3.65	34.90	27.76
840	3.51	34.885	800	3.50	34.89	27.77
1,052	3.39	34.89	1,000	3.40	34.89	27.78
1,587	3.30	34.91	1,500	3.35	34.91	27.80

Station 4638; Apr. 4; latitude 47°55.5′ N., longitude 47°35′ W.; depth 351 meters; dynamic height 970.920

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.49	33.14	0	−0.49	33.14	26.65
25	−0.29	33.50	25	−0.29	33.50	26.93
48	0.02	33.68	50	0.05	33.70	27.08
73	0.98	33.96	75	1.00	33.98	27.24
96	1.25	34.08	100	1.30	34.10	27.32
146	1.84	34.32	150	1.90	34.34	27.47
194	2.26	34.46	200	2.30	34.48	27.55
			(300)	2.90	34.68	27.66

Station 4639; Apr. 5; latitude 47°45′ N., longitude 47°43′ W.; depth 298 meters; dynamic height 970.997

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.60	33.04	0	−0.60	33.04	26.57
24	−0.83	33.16	25	−0.35	33.17	26.66
47	−1.07	33.31	50	−1.05	33.32	26.81
72	−0.75	33.38	75	−0.70	33.40	26.87
95	−0.44	33.51	100	−0.40	33.54	26.97
143	0.09	33.73	150	0.25	33.78	27.13
191	1.52	34.09	200	1.60	34.13	27.32
242	1.91	34.27	(300)	2.20	34.41	27.51

Station 4640; Apr. 5; latitude 47°42.5′ N., longitude 48°08′ W.; depth 241 meters; dynamic height 971.040

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.65	32.88	0	−0.65	32.88	26.45
23	−0.77	32.96	25	−0.75	32.97	26.52
46	−1.07	33.10	50	−1.10	33.12	26.65
69	−1.13	33.22	75	−1.15	33.26	26.77
92	−0.83	33.36	100	−0.75	33.37	26.84
139	−0.60	33.44	150	−0.50	33.48	26.92
185	0.26	33.72	200	0.55	33.81	27.14

Station 4641; Apr. 5; latitude 47°40′ N., longitude 48°30′ W.; depth 207 meters; dynamic height 971.039

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.53	32.90	0	−0.53	32.90	26.45
27	−0.53	32.97	25	−0.55	32.96	26.50
52	−0.79	33.20	50	−0.75	33.19	26.70
79	−0.91	33.30	75	−0.90	33.29	26.78
105	−0.77	33.34	100	−0.80	33.33	26.81
158	0.30	33.62	150	0.15	33.58	26.97
			(200)	0.75	33.81	27.13

Station 4642; Apr. 5; latitude 47°37′ N., longitude 48°54′ W., depth 173 meters; dynamic height 971.045

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.70	32.85	0	−0.70	32.85	26.42
27	−0.75	32.87	25	−0.75	32.86	26.43
54	−1.03	33.11	50	−1.00	33.07	26.61
81	−0.94	33.27	75	−0.95	33.24	26.75
107	−0.63	33.38	100	−0.70	33.35	26.82
162	0.46	33.63	150	0.25	33.57	26.97

Station 4643; Apr. 5; latitude 47°49′ N., longitude 48°42′ W.; depth 220 meters; dynamic height 971.048

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.54	32.89	0	−0.54	32.89	26.44
23	−0.54	32.90	25	−0.55	32.91	26.46
46	−1.05	33.05	50	−1.05	33.07	26.61
69	−1.11	--------	75	−1.10	33.19	26.71
92	−0.86	33.28	100	−0.75	33.32	26.80
138	−0.29	33.50	150	−0.05	33.56	26.97
184	0.75	33.74	(200)	1.10	33.82	27.11

STATIONS OCCUPIED IN 1952—Continued

Station 4644; Apr. 5; latitude 48°00′ N., longitude 48°32′ W.; depth 312 meters; dynamic height 971.020

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	−0.50	32.87	0	−0.50	32.87	26.43
22	−0.56	32.90	25	−0.60	32.95	26.49
44	−1.17	33.18	50	−1.15	33.20	26.72
65	−1.07	33.26	75	−0.95	33.30	26.79
87	−0.84	33.36	100	−0.60	33.44	26.89
131	0.24	33.64	150	0.95	33.79	27.09
174	1.55	33.98	200	1.70	34.10	27.29
261	1.89	34.28	(300)	2.00	34.38	27.49

Station 4645; Apr. 5; latitude 48°06.5′ N., longitude 48°27′ W.; depth 739 meters; dynamic height 970.969

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	−0.80	33.04	0	−0.80	33.04	26.58
21	−1.10	33.12	25	−1.10	33.15	26.67
42	−1.03	33.29	50	−0.90	33.34	26.83
63	−0.61	33.41	75	−0.50	33.47	26.92
84	−0.42	33.53	100	0.00	33.66	27.05
126	0.86	33.90	150	1.20	34.07	27.31
169	1.40	34.18	200	1.80	34.32	27.47
253	2.34	34.48	300	2.55	34.56	27.60
319	2.64	34.58	400	3.10	34.72	27.68
505	3.56	34.84	(600)	3.60	34.88	27.75

Station 4646; Apr. 5; latitude 48°30′ N., longitude 48°14′ W.; depth 1,962 meters; dynamic height 970.834

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.31	34.39	0	2.31	34.39	27.48
21	2.31	34.39	25	2.30	34.39	27.48
42	2.39	34.40	50	2.35	34.39	27.47
63	2.26	34.37	75	2.45	34.46	27.52
84	2.62	34.56	100	2.75	34.62	27.63
127	2.91	34.69	150	3.05	34.74	27.69
169	3.18	34.77	200	3.25	34.79	27.71
253	3.35	34.81	300	3.35	34.82	27.73
391	3.38	34.84	400	3.40	34.84	27.74
588	3.52	34.86	600	3.50	34.86	27.75
788	3.47	34.90	800	3.45	34.89	27.77
990	3.40	34.88	1,000	3.40	34.88	27.77
1,498	3.35	34.92	1,500	3.35	34.91	27.80

Station 4647; Apr. 5; latitude 48°53′ N., longitude 48°00′ W.; depth 2,320 meters; dynamic height 970.823

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	3.81	34.40	0	3.81	34.40	27.35
25	3.61	34.42	25	3.61	34.42	27.39
50	3.05	34.50	50	3.05	34.50	27.50
75	2.66	34.52	75	2.66	34.52	27.56
99	3.05	34.61	100	3.05	34.62	27.60
150	3.59	34.81	150	3.60	34.81	27.70
200	3.54	34.84	200	3.55	34.84	27.72
299	3.54	34.86	300	3.55	34.86	27.74
338	3.59	34.87	400	3.55	34.87	27.76
515	3.43	34.87	600	3.40	34.87	27.77
696	3.41	34.88	800	3.40	34.90	27.79
886	3.36	34.91	1,000	3.35	34.90	27.79
1,390	3.35	34.89	(1,500)	3.35	34.90	27.79

Station 4648; Apr. 6; latitude 49°17.5′ N., longitude 47°49′ W.; depth 2,598 meters; dynamic height 970.831

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	3.94	34.37	0	3.94	34.37	27.32
26	3.90	34.37	25	3.90	34.37	27.32
51	2.93	34.52	50	2.95	34.52	27.53
76	2.87	34.54	75	2.90	34.54	27.55
101	2.85	34.60	100	2.85	34.60	27.60
153	3.59	34.81	150	3.55	34.81	27.70
204	3.39	34.82	200	3.40	34.82	27.73
305	3.34	34.84	300	3.30	34.84	27.75
438	3.41	34.85	400	3.40	34.85	27.75
653	3.53	34.88	600	3.50	34.87	27.76
865	3.43	34.89	800	3.45	34.89	27.77
1,082	3.34	34.88	1,000	3.35	34.88	27.77
1,625	3.20	34.93	1,500	3.25	34.92	27.82

Station 4649; Apr. 6; latitude 49°41′ N., longitude 47°42′ W.; depth 2,651 meters; dynamic height 970.894

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.85	34.34	0	4.85	34.34	27.19
24	4.86	34.36	25	4.85	34.36	27.21
48	4.70	34.50	50	4.70	34.51	27.34
72	4.62	34.58	75	4.65	34.58	27.40
96	4.58	34.57	100	4.60	34.57	27.40
143	4.46	34.58	150	4.25	34.58	27.44
191	2.68	34.50	200	2.70	34.52	27.55
287	3.66	34.77	300	3.60	34.78	27.67
359	3.38	34.79	400	3.40	34.80	27.71
542	3.43	34.84	600	3.45	34.86	27.75
728	3.68	34.90	800	3.65	34.90	27.76
914	3.58	34.885	1,000	3.50	34.89	27.77
1,387	3.33	34.87	(1,500)	3.30	34.87	27.78

Station 4650; Apr. 6; latitude 49°50′ N., longitude 48°20′ W.; depth 2,561 meters; dynamic height 970.850

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.52	34.26	0	4.52	34.26	27.17
26	3.94	34.38	25	3.95	34.37	27.32
50	3.51	34.50	50	3.50	34.50	27.46
76	3.75	34.62	75	3.75	34.62	27.53
100	3.73	34.68	100	3.75	34.68	27.57
152	3.91	34.80	150	3.90	34.80	27.66
202	3.17	34.77	200	3.20	34.77	27.71
302	3.24	34.80	300	3.25	34.80	27.72
381	3.37	34.82	400	3.40	34.83	27.73
580	3.45	34.86	600	3.45	34.86	27.75
785	3.42	34.86	800	3.40	34.86	27.76
994	3.37	34.86	1,000	3.35	34.86	27.76
1,534	3.34	34.91	1,500	3.35	34.91	27.80

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4651; Apr. 6; latitude 49°59.5′ N., longitude 49°00′ W.; depth 2,607 meters; dynamic height 970.825

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	3.29	34.42	0	3.29	34.42	27.42
27	3.12	34.45	25	3.15	34.45	27.45
53	2.82	34.45	50	2.85	34.45	27.48
79	2.31	34.48	75	2.40	34.47	27.54
105	2.31	34.57	100	2.25	34.55	27.61
159	2.63	34.68	150	2.55	34.66	27.68
211	2.85	34.76	200	2.80	34.74	27.71
316	3.16	34.81	300	3.10	34.80	27.74
404	*3.45	34.86	400	3.45	34.86	27.75
611	3.37	34.87	600	3.35	34.87	27.77
824	3.31	34.87	800	3.30	34.87	27.78
1,035	3.31	34.88	1,000	3.30	34.88	27.78
1,571	3.30	34.915	1,500	3.30	34.91	27.81

Station 4652; Apr. 6; latitude 49°34′ N., longitude 49°10′ W.; depth 1,685 meters; dynamic height 970.846

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	2.09	34.30	0	2.09	34.30	27.42
28	2.04	34.39	25	2.05	34.38	27.49
57	2.04	34.44	50	2.05	34.43	27.53
85	2.27	34.50	75	2.20	34.47	27.56
114	2.62	34.59	100	2.50	34.54	27.58
171	2.90	34.70	150	2.80	34.66	27.65
228	3.35	34.80	200	3.15	34.75	27.69
342	3.46	34.83	300	3.45	34.82	27.72
475	*3.50	34.84	400	3.50	34.84	27.73
720	3.58	34.87	600	3.55	34.86	27.74
971	3.48	34.89	800	3.55	34.88	27.75
1,214	3.37	34.87	1,000	3.45	34.89	27.77
			(1,500)	3.30	34.88	27.78

Station 4653; Apr. 6; latitude 49°12.5′ N., longitude 49°19′ W.; depth 1,550 meters; dynamic height 970.851

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	2.33	34.33	0	2.33	34.33	27.42
24	2.44	34.39	25	2.45	34.38	27.45
49	2.43	34.38	50	2.45	34.38	27.45
73	2.36	34.40	75	2.35	34.40	27.48
97	2.28	34.45	100	2.30	34.46	27.54
146	2.68	34.59	150	2.70	34.60	27.61
195	2.92	34.72	200	2.95	34.73	27.69
292	3.28	34.78	300	3.30	34.79	27.71
476	3.44	34.85	400	3.45	34.83	27.72
720	3.46	34.86	600	3.45	34.86	27.75
969	3.44	34.89	800	3.45	34.87	27.76
1,198	3.34	34.88	1,000	3.40	34.89	27.78
1,585	3.32	34.90	1,500	3.30	34.90	27.80

Station 4654; Apr. 7; latitude 48°41′ N., longitude 49°31′ W.; depth 1,100 meters; dynamic height 970.926

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.28	33.45	0	−0.28	33.45	26.89
24	−0.08	33.58	25	−0.05	33.59	26.99
48	0.03	33.73	50	0.05	33.74	27.11
72	0.59	33.84	75	0.65	33.85	27.16
95	0.94	34.08	100	1.00	34.09	27.33
143	1.59	34.28	150	1.75	34.30	27.45
190	2.62	34.46	200	2.65	34.48	27.52
285	2.73	34.62	300	2.75	34.63	27.63
376	2.97	34.70	400	3.05	34.72	27.68
562	3.69	34.87	600	3.70	34.88	27.74
763	3.62	34.89	800	3.60	34.89	27.76
911	3.55	34.89	(1,000)	3.50	34.89	27.77

Station 4655; Apr. 7; latitude 48°31′ N., longitude 49°35′ W.; depth 629 meters; dynamic height 970.933

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.21	33.42	0	−0.21	33.42	26.87
24	−0.16	33.46	25	−0.10	33.57	26.98
47	0.50	33.84	50	0.50	33.85	27.17
71	0.51	33.90	75	0.55	33.91	27.22
94	0.56	33.92	100	0.60	33.94	27.23
142	1.29	34.16	150	1.50	34.20	27.39
190	2.35	34.40	200	2.40	34.42	27.50
284	2.54	34.54	300	2.70	34.58	27.59
332	2.94	34.66	400	3.30	34.78	27.70
524	3.60	34.86	(600)	3.65	34.88	27.74

Station 4656; Apr. 7; latitude 48°13′ N., longitude 49°39′ W.; depth 223 meters; dynamic height 971.054

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.72	32.76	0	−0.72	32.76	26.35
24	−0.73	32.77	25	−0.75	32.77	26.36
48	−1.00	32.81	50	−1.00	32.81	26.40
72	−1.20	32.99	75	−1.20	33.00	26.56
95	−1.11	33.19	100	−1.05	33.22	26.73
143	−0.27	33.49	150	−0.05	33.53	26.94
190	1.18	33.84	(200)	1.45	33.93	27.17

Station 4657; Apr. 7; latitude 47°58′ N., longitude 49° 42′ W.; depth 175 meters; dynamic height 971.048

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.65	32.80	0	−0.65	32.80	26.39
25	−0.69	32.82	25	−0.69	32.82	26.40
49	−1.03	32.93	50	−1.05	32.93	26.50
74	−1.08	33.12	75	−1.10	33.12	26.65
99	−1.04	33.23	100	−1.05	33.23	26.74
148	0.20	33.53	150	0.25	33.54	26.94

Station 4658; Apr. 7; latitude 47°47′ N., longitude 49°45′ W.; depth 114 meters; dynamic height 971.042

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.16	32.78	0	−0.16	32.78	26.35
23	−0.39	32.83	25	−0.45	32.85	26.42
45	−0.98	32.97	50	−1.05	32.99	26.55
68	−1.05	33.04	75	−0.90	33.09	26.62
90	−0.32	33.30	(100)	0 00	33.40	26.84

Station 4659; Apr. 7; latitude 47°21′ N., longitude 49°59′ W.; depth 94 meters; dymanic height 971.063

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	0.45	32.68	0	0.45	32.68	26.24
26	0.22	32.72	25	0 20	32.72	26.28
52	0.13	32.73	50	0.15	32.73	26.29
78	−0.29	32.82	75	−0.25	32.81	26.38

Station 4660; Apr. 7; latitude 47°33′ N., longitude 50°25′ W.; depth 123 meters; dynamic height 971.064

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	0.32	32.58	0	0.32	32.58	26.17
25	0.28	32.57	25	0.28	32.57	26.16
50	−0.03	32.71	50	−0.03	32.71	26.28
74	−0.31	32.93	75	−0.30	32.94	26.48
99	−0.28	33.10	100	−0.30	33.11	26.61

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—*Continued*

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
Station 4661; Apr. 7; latitude 47°42.5′ N., longitude 50°42′ W; depth 128 meters; dynamic height 971.057						
0	−0.09	32.74	0	−0.09	32.74	26.31
24	−0.15	32.73	25	−0.15	32.73	26.31
48	−0.29	32.74	50	−0.35	32.74	26.32
72	−0.78	32.88	75	−0.75	32.90	26.46
96	−0.40	33.10	100	−0.30	33.15	26.64
Station 4662; Apr. 8; latitude 47°50′ N., longitude 51°00′ W.; depth 123 meters; dynamic height 971.063						
0	0.10	32.61	0	0.10	32.61	26.21
25	0.02	32.61	25	0.02	32.61	26.21
51	−0.42	32.70	50	−0.35	32.70	26.28
76	−0.83	32.79	75	−0.80	32.79	26.38
102	−0.36	33.15	100	−0.40	33.13	26.64
Station 4663; Apr. 8; latitude 47°58′ N., longitude 51°20′ W.; depth 194 meters; dynamic height 971.055						
0	−0.54	32.65	0	−0.54	32.65	26.26
25	−0.58	32.67	25	−0.58	32.67	26.27
50	−0.72	32.78	50	−0.72	32.78	26.37
75	−1.07	32.98	75	−1.07	32.98	26.54
100	−0.75	33.12	100	−0.75	33.12	26.64
150	−0.36	33.29	150	−0.36	33.29	26.75
Station 4664; Apr. 8; latitude 48°06.5′ N., longitude 51°39′ W.; depth 220 meters; dynamic height 971.046						
0	−0.70	32.66	0	−0.70	32.66	26.27
25	−0.85	32.70	25	−0.85	32.70	26.30
49	−1.18	32.96	50	−1.15	32.97	26.53
74	−1.31	33.01	75	−1.30	33.01	26.57
98	−1.15	33.13	100	−1.10	33.13	26.66
147	−0.80	33.28	150	−0.75	33.29	26.77
Station 4665; Apr. 8; latitude 48°14′ N., longitude 51°58′ W.; depth 181 meters; dynamic height 971.060						
0	−0.77	32.41	0	−0.77	32.41	26.08
24	−0.89	32.44	25	−0.90	32.44	26.10
48	−1.39	32.73	50	−1.40	32.74	26.36
72	−1.50	32.84	75	−1.50	32.85	26.44
97	−1.41	33.00	100	−1.35	33.02	26.58
145	−0.33	33.34	150	−0.20	33.37	26.82
Station 4666; Apr. 8; latitude 48°23.5′ N., longitude 52°22′ W.; depth 197 meters; dynamic height 971.057						
0	−0.89	32.54	0	−0.89	32.54	26.19
23	−1.03	32.60	25	−1.05	32.60	26.24
47	−1.30	32.74	50	−1.35	32.75	26.36
70	−1.49	32.82	75	−1.50	32.85	26.44
93	−1.36	33.00	100	−1.30	33.03	26.58
140	−1.00	33.22	(150)	−0.90	33.26	26.76
Station 4667; Apr. 8; latitude 48°34′ N., 52°41′ W., longitude depth 274 meters; dynamic height 971.049						
0	−0.92	32.68	0	−0.92	32.68	26.30
24	−0.95	32.70	25	−0.95	32.70	26.31
47	−1.11	32.72	50	−1.15	32.73	26.34
71	−1.52	32.86	75	−1.50	32.89	26.47
94	−1.30	33.04	100	−1.25	33.07	26.62
141	−1.18	33.29	150	−1.00	33.33	26.82
188	−0.26	33.48	200	0.05	33.55	26.96
235	1.01	33.82				
Station 4668; Apr. 8; latitude 48°38.5′ N., longitude 52°49′ W.; depth 119 meters; dynamic height 971.054						
0	−0.97	32.61	0	−0.97	32.61	26.25
23	−1.04	32.61	25	−1.05	32.61	26.25
45	−1.20	32.65	50	−1.25	32.68	26.30
68	−1.48	32.82	75	−1.40	32.88	26.47
90	--1.03	32.99	(100)	−0.90	33.07	26.61
Station 4669; Apr. 8; latitude 48°44′ N., longitude 52°58′ W.; depth 107 meters; dynamic height 971.060						
0	−1.13	32.55	0	−1.13	32.55	26.19
25	−1.14	32.55	25	−1.14	32.55	26.19
50	−1.40	32.66	50	−1.40	32.66	26.29
75	−1.48	32.80	75	−1.48	32.80	26.41
			(100)	−1.25	32.95	26.52
Station 4670; Apr. 8; latitude 48°46′ N., longitude 52°51′ W.; depth 174 meters; dynamic height 971.049						
0	−0.79	32.65	0	−0.79	32.65	26.26
23	−0.88	32.69	25	−0.90	32.69	26.30
46	−0.97	32.71	50	−1.05	32.73	26.34
69	−1.44	32.86	75	−1.40	32.90	26.48
91	−1.33	33.03	100	−1.25	33.09	26.63
136	−0.74	33.30	(150)	−0.45	33.38	26.84
Station 4671; Apr. 8; latitude 48°48′ N., longitude 52°46′ W.; depth 229 meters; dynamic height 971.048						
0	−0.84	32.68	0	−0.84	32.68	26.29
25	−0.87	32.69	25	−0.87	32.69	26.29
49	−1.02	32.70	50	−1.00	32.70	26.31
74	−1.44	32.89	75	−1.45	32.90	26.48
98	−1.25	33.07	100	−1.25	33.10	26.64
148	−1.22	33.31	150	−1.20	33.47	26.95
197	0.48	33.70	200	0.70	33.71	27.05

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
Station 4672; Apr. 8; latitude 48°53′ N., longitude 52°30′ W.; depth 351 meters; dynamic height 971.069						
0	−0.90	32.66	0	−0.90	32.66	26.28
25	−0.91	32.66	25	−0.91	32.66	26.28
50	−1.25	32.73	50	−1.25	32.73	26.34
74	−1.44	32.89	75	−1.45	32.90	26.48
99	−1.40	33.06	100	−1.40	33.07	26.62
149	−1.73	33.29	150	−1.75	33.29	26.80
198	−0.27	33.52	200	−0.20	33.53	26.95
297	1.78	34.20	300	1.80	34.22	27.39
Station 4673; Apr. 8; latitude 48°59′ N., longitude 52°11′ W.; depth 290 meters; dynamic height 971.054						
0	−0.96	32.61	0	−0.96	32.61	26.25
25	−0.85	32.69	25	−0.85	32.69	26.29
50	−1.06	32.72	50	−1.06	32.72	26.33
75	−1.49	33.01	75	−1.49	33.01	26.58
100	−1.29	33.15	100	−1.29	33.15	26.68
150	−1.71	33.30	150	−1.71	33.30	26.81
200	0.45	33.68	200	0.45	33.68	27.03
280	2.38	34.52				
Station 4674; Apr. 8; latitude 49°03.5′ N., longitude 51°57′ W.; depth 297 meters; dynamic height 971.011						
0	−1.28	32.68	0	−1.28	32.68	26.30
24	−1.49	32.74	25	−1.50	32.74	26.36
48	−1.60	33.17	50	−1.60	33.18	26.71
72	−1.56	33.28	75	−1.50	33.29	26.80
95	−1.05	33.36	100	−1.05	33.37	26.85
143	−1.45	33.44	150	−1.35	33.47	26.95
191	0.73	33.86	200	0.90	33.92	27.21
272	1.74	34.26				
Station 4675; Apr. 8; latitude 49°10′ N., longitude 51°36′ W.; depth 284 meters; dynamic height 970.983						
0	−0.58	33.03	0	−0.58	33.03	26.56
23	−0.74	33.14	25	−0.75	33.15	26.66
46	−0.92	33.24	50	−0.90	33.26	26.76
70	−0.94	33.32	75	−0.90	33.34	26.83
93	−0.76	33.43	100	−0.70	33.46	26.92
139	−0.20	33.67	150	0.15	33.73	27.09
185	1.17	33.98	200	1.40	34.06	27.28
241	1.86	34.26				
Station 4676; Apr. 9; latitude 49°19.5′ N., longitude 51°06′ W.; depth 326 meters; dynamic height 970.935						
0	−0.39	33.32	0	−0.39	33.32	26.79
25	−0.29	33.38	25	−0.29	33.38	26.83
49	−0.55	33.57	50	−0.55	33.57	27.00
74	−0.40	33.62	75	−0.35	33.62	27.03
99	−0.03	33.70	100	0.00	33.70	27.08
148	1.10	34.06	150	1.15	34.08	27.31
197	1.78	34.32	200	1.80	34.33	27.47
296	2.74	34.61	300	2.80	34.62	27.62
Station 4677; Apr. 9; latitude 49°28′ N., longitude 50°39′ W.; depth 335 meters; dynamic height 970.908						
0	−0.35	33.37	0	−0.35	33.37	26.82
25	−0.47	33.45	25	−0.47	33.45	26.90
50	−0.42	33.59	50	−0.42	33.59	27.01
74	0.35	33.76	75	0.35	33.77	27.12
99	0.99	33.99	100	1.00	33.99	27.25
149	0.83	34.14	150	0.85	34.15	27.39
			(200)	1.85	34.52	27.62
			(300)	2.95	34.69	27.66
Station 4678; Apr. 9; latitude 49°40′ N., longitude 50°02′ W.; depth 620 meters; dynamic height 970.861						
0	1.21	34.00	0	1.21	34.00	27.25
25	0.95	34.00	25	0.95	34.00	27.26
49	0.83	34.06	50	0.85	34.07	27.33
74	1.14	34.18	75	1.15	34.19	27.40
98	1.62	34.32	100	1.65	34.33	27.48
148	1.98	34.46	150	2.00	34.47	27.57
198	2.50	34.57	200	2.50	34.58	27.61
296	2.93	34.71	300	2.95	34.72	27.69
401	3.31	34.81	400	3.20	34.81	27.74
596	3.46	34.89	600	3.45	34.89	27.77
Station 4679; Apr. 9; latitude 49°48′ N., longitude 49°31′ W.; depth 1,340 meters; dynamic height 970.888						
0	0.84	33.90	0	0.84	33.90	27.19
25	0.83	33.91	25	0.83	33.91	27.20
49	0.70	34.06	50	0.70	34.06	27.33
74	1.03	34.14	75	1.05	34.15	27.38
98	1.48	34.32	100	1.50	34.33	27.49
147	1.97	34.46	150	2.00	34.46	27.56
196	1.96	34.49	200	2.00	34.50	27.59
294	3.35	34.73	300	3.35	34.73	27.65
383	3.35	34.78	400	3.35	34.79	27.70
577	3.40	34.84	600	3.40	34.85	27.75
772	3.53	34.88	800	3.55	34.88	27.75
968	3.57	34.885	1,000	3.55	34.89	27.76
1,264	3.35	34.90				
Station 4680; Apr. 9; latitude 50°00′ N., longitude 49°00′ W.; depth 1,905 meters; dynamic height 970.815						
0	3.49	34.43	0	3.49	34.43	27.40
24	3.29	34.44	25	3.30	34.44	27.43
47	2.54	34.50	50	2.55	34.52	27.57
70	3.04	34.65	75	3.00	34.65	27.63
93	2.49	34.63	100	2.60	34.66	27.67
140	3.43	34.82	150	3.45	34.82	27.72
186	3.41	34.83	200	3.45	34.84	27.73
279	3.70	34.89	300	3.60	34.88	27.75
324	3.41	34.86	400	3.35	34.85	27.75
488	3.30	34.845	600	3.30	34.86	27.77
654	3.32	34.87	800	3.30	34.88	27.78
826	3.32	34.88	1,000	3.30	34.89	27.79
1,271	3.32	34.90	(1,500)	3.30	34.90	27.80

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4681; Apr. 9; latitude 50°17′ N., longitude 50°06′ W.; depth 1,074 meters; dynamic height 1454.649

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	1.14	33.99	0	1.14	33.99	27.24
24	1.12	34.04	25	1.10	34.04	27.29
48	1.32	34.12	50	1.35	34.14	27.35
72	1.55	34.27	75	1.55	34.27	27.44
96	1.54	34.30	100	1.55	34.31	27.47
142	1.80	34.41	150	1.85	34.43	27.54
190	2.13	34.49	200	2.20	34.51	27.59
286	3.01	34.68	300	3.05	34.70	27.66
360	3.09	34.73	400	3.20	34.76	27.70
539	3.52	34.85	600	3.55	34.86	27.74
716	3.62	34.88	800	3.55	34.89	27.76
908	3.48	34.89	(1,000)	3.45	34.89	27.77

Station 4682; Apr. 9; latitude 50°38.5′ N., longitude 50°50′ W.; depth 370 meters; dynamic height 1,454.657

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	−0.15	33.40	0	−0.15	33.40	26.85
20	0.52	33.79	25	0.50	33.80	27.13
41	0.40	33.81	50	0.40	33.85	27.18
61	0.38	33.91	75	0.65	34.01	27.29
82	0.80	34.06	100	1.10	34.16	27.39
122	1.39	34.27	150	1.90	34.37	27.50
163	2.05	34.41	200	2.40	34.53	27.58
245	2.72	34.64	300	3.05	34.74	27.69

Station 4683; Apr. 10; latitude 50°36.5′ N., longitude 50°40′ W.; depth 704 meters; dynamic height 1,454.642

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	−0.26	33.34	0	−0.26	33.34	26.80
20	−0.24	33.54	25	−0.10	33.63	27.02
39	0.37	33.94	50	0.65	34.08	27.34
59	0.96	------	75	1.35	34.25	27.44
78	1.44	34.28	100	1.70	34.35	27.49
116	1.84	34.40	150	2.20	34.49	27.57
155	2.25	34.50	200	2.50	34.61	27.64
210	*2.53	34.63	300	3.05	34.75	27.70
360	3.33	34.80	400	3.45	34.83	27.72
508	3.58	34.88	(600)	3.55	34.89	27.76

Station 4684; Apr. 10; latitude 50°34′ N., lontitude 50°23′ W.; depth 1,060 meters; dynamic height 1,454.694

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	−0.73	33.23	0	−0.73	33.23	26.73
23	−0.64	33.41	25	−0.55	33.43	26.88
44	0.11	33.67	50	0.20	33.72	27.09
67	0.33	33.86	75	0.35	33.90	27.22
89	0.34	33.94	100	0.45	33.99	27.28
134	1.09	34.20	150	1.50	34.29	27.46
178	2.08	34.42	200	2.30	34.49	27.56
267	2.70	34.61	300	2.90	34.67	27.66
267	2.76	34.63	400	3.25	34.76	27.69
413	3.29	34.77	600	3.55	34.85	27.73
567	3.50	34.84	(800)	3.60	34.88	27.75
733	3.58	34.88	(1,000)	3.50	34.89	27.77

Station 4685; Apr. 10; latitude 50°26.5′ N., longitude 49°28′ W.; depth, 1,609 meters, dynamic height 1,454.596

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	3.09	34.35	0	3.09	34.35	27.38
24	3.28	34.38	25	3.30	34.38	27.38
47	3.13	34.44	50	3.10	34.45	27.46
71	2.54	34.52	75	2.45	34.52	27.57
94	2.22	34.52	100	2.25	34.52	27.59
141	2.59	34.63	150	2.65	34.65	27.66
188	2.96	34.72	200	3.05	34.74	27.69
282	3.46	------	300	3.45	34.83	27.72
289	3.38	34.82	400	3.40	34.86	27.76
443	3.36	34.86	600	3.40	34.86	27.76
606	3.38	34.86	800	3.30	34.87	27.78
774	3.33	34.87	1,000	3.30	34.88	27.78
1,185	3.31	34.89	(1,500)	3.30	34.90	27.80

Station 4686; Apr. 10; latitude 50°16′ N., longitude 48°23′ W.; depth 2,469 meters; dynamic height 1,454.606

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	4.65	34.32	0	4.65	34.32	27.20
23	4.33	34.32	25	4.25	34.32	27.24
46	3.51	34.52	50	3.45	34.53	27.48
69	2.99	34.55	75	2.85	34.55	27.56
92	2.34	34.54	100	2.45	34.55	27.59
139	3.01	34.72	150	3.00	34.73	27.69
185	2.97	34.74	200	3.00	34.75	27.71
277	3.30	34.82	300	3.40	34.84	27.74
361	3.49	34.86	400	3.50	34.86	27.75
541	3.46	34.87	600	3.45	34.87	27.76
722	3.47	34.88	800	3.45	34.88	27.76
912	3.42	34.89	1,000	3.40	34,89	27.78
1,406	3.36	34.90	(1,500)	3.35	34.90	27.79

Station 4687; Apr. 10; latitude 50°07.5′ N., longitude 47°18′ W.; depth 2,834 meters; dynamic height 1,454.611

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	5.00	34.27	0	5.00	34.27	27.12
14	4.93	34.27	25	4.75	34.28	27.15
28	4.71	34.29	50	3.90	34.45	27.38
42	3.99	34.44	75	2.80	34.44	27.47
56	3.86	34.45	100	2.45	34.52	27.57
85	2.35	34.44	150	2.60	34.69	27.69
113	2.49	34.61	200	2.85	34.76	27 73
169	2.64	34.72	300	3.45	34.84	27.73
278	3.47	34.83	400	3.40	34.84	27.74
430	3.37	34.84	600	3.40	34.87	27.77
592	3.41	34.87	800	3.30	34.87	27.78
761	3.31	34.87	1,000	3.30	34.87	27.78
1,216	3.28	34.87	(1,500)	3.25	34.88	27.78

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4688; Apr. 10; latitude 49°58′ N., longitude 46°14′ W.; depth 3,110 meters; dynamic height 1,454.744

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	7.75	34.71	0	7.75	34.71	27.10
23	7.74	34.72	25	7.75	34.72	27.11
45	7.76	34.72	50	7.75	34.72	27.11
67	7.77	34.72	75	7.75	34.72	27.11
89	------	34.72	100	7.75	34.72	27.11
135	7.76	34.72	150	7.80	34.78	27.15
180	8.02	34.98	200	7.55	34.96	27.33
269	5.82	34.88	300	5.35	34.86	27.54
286	5.52	34.86	400	4.55	34.91	27.68
434	4.33	34.92	600	3.65	34.87	27.74
588	3.68	34.87	800	3.60	34.89	27.76
756	3.63	34.89	1,000	3.55	34.90	27.77
1,212	3.42	34.90	(1,500)	3.35	34.90	27.79

Station 4689; Apr. 11; latitude 49°48′ N., longitude 44°51′ W.; depth 2,380 meters; dynamic height 1,454.645

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.09	34.17	0	6.09	34.17	26.91
29	6.06	34.18	25	6.05	34.18	26.92
57	4.01	34.38	50	4.50	34.31	27.21
85	4.06	34.61	75	4.05	34.54	27.43
113	3.66	34.62	100	3.80	34.61	27.52
170	4.08	34.78	150	3.95	34.73	27.59
227	4.26	34.87	200	4.20	34.84	27.66
340	3.71	34.85	300	3.85	34.86	27.71
437	3.67	34.88	400	3.70	34.86	27.73
655	3.64	34.90	600	3.65	34.90	27.76
873	3.50	34.89	800	3.55	34.90	27.77
1,094	3.38	34.885	1,000	3.45	34.89	27.77
1,652	3.36	34.93	1,500	3.35	34.91	27.80

Station 4690; Apr. 11; latitude 50°35.5′ N., longitude 44°59′ W.; depth 4,024 meters; dynamic height 1,454.701

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	8.44	34.62	0	8.44	34.62	26.93
23	6.31	34.41	25	6.20	34.39	27.06
45	5.64	34.35	50	5.55	34.35	27.12
68	5.31	34.36	75	5.30	34.36	27.15
91	5.28	34.38	100	5.30	34.42	27.20
137	5.55	34.70	150	5.25	34.70	27.43
182	4.40	34.70	200	4.40	34.71	27.53
273	4.40	34.81	300	3.65	34.76	27.65
296	3.66	34.76	400	3.90	34.86	27.71
450	3.94	34.88	600	3.70	34.89	27.75
610	3.71	34.89	800	3.55	34.89	27.76
785	3.56	34.89	1,000	3.45	34.89	27.77
1,262	3.39	34.89	(1,500)	3.35	34.89	27.78

Station 4691; Apr. 11; latitude 50°42′ N., longitude 45°54′ W.; depth 3,585 meters; dynamic height 1,454.652

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.79	34.33	0	6.79	34.33	26.93
26	6.63	34.34	25	6.65	34.34	26.96
51	5.47	34.36	50	5.50	34.36	27.13
77	5.15	34.40	75	5.20	34.40	27.20
102	3.94	34.50	100	4.00	34.49	27.40
155	3.09	34.60	150	3.10	34.59	27.57
206	3.12	34.67	200	3.10	34.66	27.63
308	3.31	------	300	3.30	34.77	27.70
414	3.45	34.84	400	3.45	34.83	27.72
616	3.35	34.86	600	3.35	34.86	27.76
817	3.40	34.88	800	3.40	34.88	27.77
1,022	3.35	34.89	1,000	3.35	34.89	27.78
1,539	3.34	34.91	1,500	3.30	34.91	27.81

Station 4692; Apr. 11; latitude 50°47′ N., longitude 46°44′ W.; depth 2,158 meters; dynamic height 1,454.627

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.94	34.34	0	4.94	34.34	27.18
25	4.79	34.34	25	4.79	34.34	27.19
49	4.45	34.40	50	4.40	34.41	27.30
74	3.54	34.51	75	3.50	34.52	27.48
98	3.06	34.58	100	3.05	34.58	27.56
148	3.90	34.68	150	3.10	34.68	27.64
196	3.20	34.76	200	3.20	34.76	27.70
294	3.46	34.80	300	3.45	34.80	27.70
349	3.48	34.84	400	3.50	34.84	27.73
529	3.38	34.85	600	3.35	34.85	27.75
714	3.30	34.86	800	3.30	34.86	27.77
900	3.33	34.86	1,000	3.30	34.86	27.77
1,377	3.33	34.88	(1,500)	3.30	34.89	27.79

Station 4693; Apr. 11–12; latitude 50°52.5′ N., longitude 47°35′ W.; depth 2,743 meters; dynamic height 1,454.589

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	3.74	34.44	0	3.74	34.44	27.38
21	3.60	34.44	25	3.50	34.45	27.42
42	2.89	34.55	50	2.80	34.56	27.57
63	2.70	34.59	75	2.70	34.61	27.62
84	2.68	34.62	100	2.75	34.65	27.65
126	2.94	34.70	150	3.00	34.74	27.70
168	3.02	34.77	200	3.15	34.80	27.73
252	3.36	34.83	(300)	3.40	34.84	27.74
			(400)	3.40	34.85	27.75
			(600)	3.30	34.86	27.77
			(800)	3.30	34.86	27.77
			(1,000)	3.30	34.87	27.78
			(1,500)	3.25	34.88	27.78

STATIONS OCCUPIED IN 1952—Continued

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
Station 4694; Apr. 12; latitude 50°58′ N., longitude 48°25′ N.; depth 2,740 meters; dynamic height 1,454.581						
0	3.34	34.46	0	3.34	34.46	27.44
24	3.32	34.46	25	3.30	34.46	27.45
47	2.95	34.52	50	2.95	34.53	27.53
71	2.83	34.61	75	2.80	34.61	27.61
94	2.45	34.63	100	2.45	34.64	27.66
141	2.70	34.71	150	2.80	34.72	27.70
188	3.22	34.78	200	3.20	34.79	27.72
282	3.22	34.82	300	3.20	34.83	27.75
418	3.27	34.84	400	3.25	34.84	27.75
629	3.30	34.86	600	3.30	34.86	27.77
838	3.30	34.875	800	3.30	34.87	27.78
1,053	3.27	34.87	1,000	3.25	34.87	27.78
1,597	3.30	34.915	1,500	3.30	34.90	27.80
Station 4695; Apr. 12; latitude 50°59′ N., longitude 49°26′ W.; depth 1,554 meters; dynamic height 1,454.574						
0	3.07	34.46	0	3.07	34.46	27.47
24	2.79	34.48	25	2.80	34.48	27.50
48	2.61	34.57	50	2.60	34.57	27.60
72	2.46	34.60	75	2.45	34.60	27.63
95	2.51	34.65	100	2.50	34.65	27.67
143	2.60	34.70	150	2.65	34.71	27.71
191	2.96	34.77	200	3.00	34.78	27.73
286	3.22	34.83	300	3.25	34.84	27.75
332	3.26	34.85	400	3.35	34.87	27.77
488	3.42	34.875	600	3.35	34.88	27.77
637	3.31	34.875	800	3.30	34.88	27.78
810	3.30	34.88	1,000	3.30	34.88	27.78
1,271	3.29	34.89	(1,500)	3.25	34.90	27.80
Station 4696; Apr. 12; latitude 50°59′ N., longitude 49°43′ W.; depth 1,122 meters; dynamic height 1,454.618						
0	0.61	33.73	0	0.61	33.73	27.06
25	0.74	34.06	25	0.74	34.06	27.33
48	1.50	34.24	50	1.50	34.25	27.43
73	1.51	34.31	75	1.55	34.31	27.47
96	2.01	34.42	100	2.05	34.43	27.53
145	2.27	34.54	150	2.30	34.55	27.61
194	2.58	34.66	200	2.60	34.67	27.68
290	3.23	34.79	300	3.30	34.80	27.72
378	3.47	34.84	400	3.50	34.85	27.74
570	3.47	34.875	600	3.45	34.88	27.76
764	3.36	34.88	800	3.35	34.88	27.77
961	3.30	34.88	(1,000)	3.30	34.88	27.78
Station 4697; Apr. 12; latitude 50°59′ N., longitude 49°49′ W.; depth 1,035 meters; dynamic height 1,454.658						
0	−0.12	33.41	0	−0.12	33.41	26.85
22	0.36	33.76	25	0.40	33.78	27.12
44	0.42	33.94	50	0.60	33.98	27.26
66	1.05	34.12	75	1.20	34.18	27.39
88	1.39	34.26	100	1.60	34.31	27.47
132	2.06	34.42	150	2.15	34.47	27.56
176	2.29	34.53	200	2.50	34.58	27.61
264	2.97	34.68	300	3.15	34.73	27.67
336	3.29	34.77	400	3.45	34.81	27.71
510	3.57	34.85	600	3.60	34.87	27.75
688	3.62	34.895	800	3.55	34.88	27.75
822	3.54	34.88	(1,000)	3.45	34.88	27.76

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
Station 4698; Apr. 12; latitude 51°29′ N., longitude 50°21′ W.; depth 406 meters; dynamic height 1,454.608						
0	−0.27	33.30	0	−0.27	33.30	26.76
17	−0.13	33.63	25	0.30	33.76	27.11
35	1.01	33.88	50	0.45	34.01	27.30
52	0.45	34.03	75	0.70	34.10	27.36
69	0.62	34.08	100	1.20	34.23	27.43
104	1.30	34.26	150	2.10	34.49	27.57
139	1.92	34.46	200	2.60	34 61	27.63
208	2.69	34.62	(300)	2.90	34.74	27.71
274	2.82	34.71	(400)	3.15	34.85	27.77
Station 4699; Apr. 13; latitude 51°29′ N., longitude 50°11′ W.; depth 685 meters; dynamic height 1,454.582						
0	0.47	33.92	0	0.47	33.92	27.23
22	0.47	33.92	25	0.45	33.94	27.24
44	0.56	34.14	50	0.75	34.18	27.42
65	1.38	34.25	75	1.40	34.28	27.46
87	1.40	34.32	100	1.65	34.37	27.52
131	2.12	34.50	150	2.30	34.56	27.62
174	2.47	34.62	200	2.60	34.67	27.68
261	2.97	34.75	300	3.10	34.80	27.74
291	3.08	34.80	400	3.10	34.84	27.77
462	*3.10	34.86	(600)	3.10	34.87	27.80
Station 4700; Apr. 13; latitude 51°28.5′ N. longitude 49°55′ W.; depth 1,742 meters; dynamic height 1,454.574						
0	2.76	34.50	0	2.76	34.50	27.53
25	2.73	34.52	25	2.73	34.52	27.55
50	2.63	34.52	50	2.63	34.52	27.56
75	2.43	34.61	75	2.43	34.61	27.64
100	2.52	34.63	100	2.52	34.63	27.65
150	2.87	34.76	150	2.87	34.76	27.73
200	3.04	34.79	200	3.04	34.79	27.73
300	3.21	34.83	300	3.21	34.83	27.75
366	3.41	34.85	400	3.40	34.86	27.76
549	3.42	34.87	600	3.40	34.87	27.77
733	3.36	34.88	800	3.35	34.88	27.77
921	3.31	34.87	1,000	3.30	34.87	27.78
1,399	3.33	34.91	1,500	3.30	34.91	27.81
Station 4701; Apr. 13; latitude 51°27′ N., longitude 49°15′ W.; depth 2,561 meters; dynamic height 1,454.590						
0	1.55	34.18	0	1.55	34.18	27.36
25	1.64	34.22	25	1.64	34.22	27.40
49	1.86	34.27	50	1.85	34.27	27.42
73	2.05	34.48	75	2.05	34.49	27.58
97	2.20	34.55	100	2.20	34.56	27.63
147	2.67	34.67	150	2.70	34.68	27.67
196	2.85	34.71	200	2.85	34.71	27.69
293	3.13	34.80	300	3.10	34.80	27.74
323	3.14	34.81	400	3.25	34.85	27.76
490	3.34	34.87	600	3.35	34.87	27.77
662	3.34	34.87	800	3.30	34.88	27.78
839	3.33	34.89	1,000	3.30	34.89	27.79
1,299	------	34.89	1,500	3.30	34.89	27.79

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4702; Apr. 13; latitude 51°26′ N., longitude 48°24′ W.; depth 3,200 meters; dynamic height 1,454.685

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	6.25	34.44	0	6.25	34.44	27.10
25	6.25	34.44	25	6.25	34.44	27.10
49	6.28	34.43	50	6.25	34.44	27.10
74	5.86	34.64	75	5.85	34.64	27.31
99	5.46	34.66	100	5.45	34.66	27.37
149	5.30	34.70	150	5.30	34.70	27.42
198	4.76	34.70	200	4.75	34.70	27.49
297	4.27	34.84	300	4.25	34.84	27.65
432	2.77	34.785	400	3.20	34.80	27.73
618	3.49	34.87	600	3.45	34.87	27.76
787	3.59	34.89	800	3.60	34.89	27.76
986	3.47	34.88	1,000	3.45	34.88	27.76
1,487	3.37	34.89	1,500	3.35	34.89	27.78

Station 4703; Apr. 14; latitude 51°26′ N., longitude 47°33′ W.; depth 3,475 meters; dynamic height 1,454.708

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	8.92	--------	0	8.92	34.67	26.90
22	8.91	34.67	25	8.90	34.67	26.90
44	8.89	34.67	50	8.80	34.67	26.91
66	8.13	34.60	75	6.95	34.53	27.07
88	5.17	34.41	100	5.10	34.48	27.27
132	4.97	34.66	150	4.75	34.67	27.47
176	4.51	34.68	200	4.50	34.72	27.53
264	4.42	34.81	300	4.05	34.81	27.65
353	3.49	34.80	400	3.55	34.82	27.71
531	3.73	34.87	600	3.70	34.88	27.74
710	3.65	34.89	800	3.60	34.88	27.75
891	3.53	34.87	1,000	3.50	34.87	27.76
1,354	3.37	34.88	(1,500)	3.30	34.89	27.79

Station 4704; Apr. 14; latitude 51°27′ N., longitude 46°45′ W.; depth 4,207 meters, dynamic height 1,454.692

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	7.18	34.44	0	7.18	34.44	26.97
24	7.16	34.44	25	7.15	34.44	26.98
49	7.12	34.44	50	7.10	34.44	26.98
73	4.97	34.45	75	4.95	34.46	27.28
98	4.72	34.57	100	4.70	34.57	27.39
146	4.52	34.68	150	4.50	34.69	27.50
194	3.99	34.72	200	3.95	34.73	27.59
292	4.15	34.85	300	4.15	34.85	27.67
384	3.80	34.86	400	3.80	34.86	27.72
573	3.74	34.88	600	3.75	34.88	27.73
761	3.59	34.87	800	3.60	34.87	27.75
952	3.53	34.865	1,000	3.50	34.87	27.76
1,431	3.35	34.88	(1,500)	3.35	34.88	27.77

Station 4705; Apr. 14; latitude 51°23.5′ N., longitude 45°53′ W.; depth 3,841 meters; dynamic height 1,454.665

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ
0	6.78	34.42	0	6.78	34.42	27.01
22	6.72	34.42	25	6.70	34.42	27.03
45	6.68	34.41	50	6.55	34.40	27.03
67	5.12	34.38	75	5.05	34.41	27.23
90	4.88	34.52	100	4.70	34.52	27.35
134	3.60	34.53	150	3.70	34.60	27.52
178	3.86	34.72	200	3.80	34.75	27.63
268	3.62	34.81	300	3.75	34.84	27.70
324	3.78	34.86	400	3.80	34.88	27.73
491	3.79	34.89	600	3.75	34.90	27.75
663	3.70	34.90	800	3.60	34.90	27.77
842	3.54	34.90	1,000	3.50	34.90	27.78
1,311	3.38	34.885	(1,500)	3.30	34.89	27.79

Station 4706; Apr. 14; latitude 51°20′ N., longitude 45°00′ W.; depth 4,024 meters; dynamic height 1,454.678

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ
0	5.68	34.32	0	5.68	34.32	27.08
26	5.33	34.31	25	5.35	34.31	27.11
51	5.31	34.32	50	5.30	34.32	27.12
77	5.20	34.35	75	5.25	34.35	27.15
102	4.51	34.52	100	4.55	34.50	27.35
153	4.08	34.72	150	4.10	34.71	27.57
204	3.87	34.78	200	3.90	34.78	27.64
306	3.89	34.83	300	3.90	34.83	27.68
338	4.11	34.89	400	4.00	34.89	27.72
519	3.70	34.88	600	3.65	34.88	27.74
709	3.59	34.88	800	3.55	34.875	27.75
910	3.51	34.87	1,000	3.50	34.875	27.76
1,450	3.39	34.89	1,500	3.40	34.89	27.78

Station 4707; Apr. 14; latitude 52°06′ N., longitude 45°29′ W.; depth 4,207 meters; dynamic height 1,454.813

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ
0		34.87	0	9.80	34.86	26.90
23	9.78	34.86	25	9.80	34.86	26.90
44	9.76	34.86	50	9.60	34.85	26.92
67	9.12	34.83	75	8.70	34.77	27.01
89	8.03	34.68	100	8.00	34.69	27.05
134	7.88	34.75	150	7.80	34.79	27.16
178	7.61	34.83	200	7.20	34.80	27.25
267	5.60	34.70	300	5.55	34.77	27.45
292	5.55	34.76	400	5.30	34.90	27.58
449	5.04	34.93	600	3.65	34.82	27.70
615	3.55	34.82	800	3.70	34.87	27.74
794	3.66	34.87	1,000	3.60	34.87	27.75
1,286	3.49	34.88	(1,500)	3.45	34.89	27.77

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
Station 4708; Apr. 15; latitude 52°03.5′ N., longitude 46°20′ W.; depth 3,987 meters; dynamic height 1,454.833						
0	10.41	34.95	0	10.41	34.95	26.86
25	10.39	34.95	25	10.39	34.95	26.86
49	10.39	34.96	50	10.40	34.96	26.87
74	10.35	34.945	75	10.35	34.95	26.87
98	10.12	34.91	100	10.10	34.91	26.89
148	8.99	34.86	150	8.95	34.86	27.04
197	8.78	34.98	200	8.75	34.98	27.16
295	4.06	34.56	300	4.05	34.57	27.46
378	5.20	34.87	400	5.00	34.87	27.60
575	3.59	34.83	600	3.60	34.83	27.71
778	3.79	34.88	800	3.80	34.88	27.73
979	3.62	34.88	1,000	3.60	34.88	27.75
1,494	3.41	34.88	1,500	3.40	34.88	27.77
Station 4709; Apr. 15; latitude 51°57.5′ N., longitude 47°09′ W.; depth 3,731 meters; dynamic height 1,454.738						
0	9.56	34.84	0	9.56	34.84	26.92
26	9.55	34.84	25	9.55	34.84	26.92
50	9.52	34.84	50	9.50	34.84	26.93
76	9.53	34.86	75	9.50	34.86	26.95
100	7.18	34.58	100	7.20	34.58	27.08
151	4.37	34.48	150	4.35	34.48	27.35
202	5.16	34.80	200	5.15	34.80	27.52
302	5.02	34.92	300	5.05	34.92	27.63
402	4.11	34.86	400	4.15	34.86	27.68
602	3.85	34.88	600	3.85	34.88	27.72
802	3.72	34.915	800	3.75	34.91	27.76
1,008	3.57	34.89	1,000	3.60	34.89	27.76
1,534	3.41	34.89	1,500	3.40	34.89	27.78
Station 4710; Apr. 15; latitude 51°57′ N., longitude 48°00′ W.; depth 3,603 meters; dynamic height 1,454.683						
0	8.71	34.68	0	8.71	34.68	26.93
24	6.47	34.44	25	6.40	34.43	27.07
47	6.15	34.41	50	6.15	34.41	27.09
71	6.09	34.42	75	6.00	34.44	27.13
94	5.26	34.59	100	5.20	34.61	27.37
141	4.82	34.69	150	4.75	34.70	27.49
188	4.43	34.75	200	4.40	34.77	27.58
282	4.33	34.86	300	4.25	34.86	27.67
334	4.05	34.86	400	4.00	34.87	27.71
509	3.89	34.90	600	3.80	34.90	27.75
690	3.69	34.89	800	3.60	34.89	27.76
881	3.57	34.89	1,000	3.55	34.90	27.77
1,393	3.42	34.90	(1,500)	3.40	34.90	27.79

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
Station 4711; Apr. 15; latitude 51°56′ N., longitude 48°48′ W.; depth 3,292 meters; dynamic height 1,454.674						
0	5.94	34.42	0	5.94	34.42	27.12
25	5.85	34.43	25	5.85	34.42	27.14
48	5.81	34.42	50	5.80	34.42	27.14
73	4.51	34.41	75	4.50	34.42	27.30
97	5.03	34.62	100	5.00	34.62	27.40
146	4.96	34.64	150	4.90	34.64	27.42
194	3.69	34.62	200	3.65	34.63	27.54
291	3.36	34.72	300	3.35	34.72	27.65
395	3.10	34.75	400	3.10	34.75	27.70
59[illegible]	3.33	34.84	600	3.35	34.84	27.74
805	3.34	34.88	800	3.35	34.88	27.77
1,016	3.29	34.87	1,000	3.30	34.87	27.78
1,564	3.27	34.87	1,500	3.25	34.87	27.78
Station 4712; Apr. 15; latitude 51°56.5′ N., longitude 49°40′ W.; depth 2,743 meters; dynamic height 1,454.580						
0	3.52	34.54	0	3.52	34.54	27.49
25	3.48	34.54	25	3.48	34.54	27.49
49	3.41	34.54	50	3.40	34.54	27.50
74	3.11	34.61	75	3.10	34.61	27.59
99	3.19	34.71	100	3.20	34.71	27.66
147	3.11	34.74	150	3.10	34.74	27.69
196	3.22	34.81	200	3.20	34.81	27.74
295	3.50	34.88	300	3.50	34.88	27.76
391	*3.48	34.86	400	3.40	34.86	27.76
587	3.31	34.86	600	3.30	34.86	27.77
785	3.35	34.86	800	3.35	34.87	27.77
983	3.27	34.88	1,000	3.30	34.88	27.78
1,484	3.33	34.90	1,500	3.30	34.90	27.80
Station 4713; Apr. 15-16; latitude 51°56.5′ N., longitude 50°21′ W.; depth 2.012 meters; dynamic height 1,454.577						
0	3.08	34.53	0	3.08	34.53	27.52
22	2.61	34.54	25	2.55	34.54	27.58
44	2.20	34.54	50	2.20	34.55	27.62
66	2.18	34.58	75	2.15	34.60	27.66
88	2.21	34.61	100	2.30	34.64	27.68
132	2.66	34.71	150	2.85	34.75	27.72
176	3.15	34.81	200	3.35	34.82	27.73
264	3.48	34.83	300	3.55	34.83	27.73
337	3.55	34.85	400	3.50	34.86	27.75
525	3.31	34.88	600	3.30	34.88	27.78
727	3.30	34.88	800	3.30	34.88	27.78
908	3.32	34.88	1,000	3.30	34.88	27.78
1,365	3.35	34.88	(1,500)	3.35	34.89	27.78

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4714; Apr. 16; latitude 51°56.5′ N., longitude 50°44′ W.; depth 622 meters; dynamic height 1,454.630

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	0.92	33.82	0	0.92	33.82	27.13
20	1.00	33.89	25	1.00	33.92	27.20
41	0.90	34.06	50	1.05	34.16	27.39
61	1.38	34.27	75	1.50	34.31	27.48
81	1.59	34.33	100	1.70	34.38	27.51
122	1.82	34.44	150	1.95	34.50	27.60
162	2.03	34.52	200	2.35	34.59	27.63
243	2.75	34.66	300	3.45	34.78	27.68
306	3.49	34.79	400	3.40	34.82	27.73
507	3.29	34.84	(600)	3.25	34.85	27.76

Station 4715; Apr. 16; latitude 51°58′ N., longitude 51°30′ W.; depth 352 meters; dynamic height 1,454.712

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.65	33.06	0	−0.65	33.06	26.59
24	−0.84	33.19	25	−0.85	33.20	26.71
47	−1.14	33.38	50	−1.15	33.40	26.89
71	−1.12	33.52	75	−1.05	33.54	26.99
95	−0.44	33.69	100	−0.30	33.73	27.11
142	0.72	34.04	150	0.85	34.07	27.33
189	1.26	34.24	200	1.40	34.28	27.46
284	2.47	34.59	(300)	2.70	34.65	27.65

Station 4716; Apr. 16; latitude 52°26′ N., longitude 51°36′ W.; depth 320 meters; dynamic height 1,454.661

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	0.35	33.84	0	0.35	33.84	27.17
23	0.65	33.89	25	0.65	33.89	27.19
46	0.66	33.92	50	0.65	33.92	27.22
69	0.67	33.95	75	0.65	33.97	27.26
93	0.40	34.04	100	0.45	34.06	27.34
139	0.99	34.18	150	1.15	34.22	27.43
185	1.61	34.35	200	1.80	34.40	27.53
278	2.75	34.65	(300)	3.00	34.71	27.68

Station 4717; Apr. 16; latitude 52°26.5′ N., longitude 51°22′ W.; depth 622 meters; dynamic height 1,454.637

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	−0.15	33.75	0	−0.15	33.75	27.13
23	0.45	33.90	25	0.50	33.90	27.21
46	0.61	33.92	50	0.60	33.92	27.22
69	0.69	33.93	75	0.75	33.95	27.24
91	1.06	34.17	100	1.20	34.22	27.43
137	1.81	34.43	150	2.05	34.49	27.58
183	2.56	34.64	200	2.70	34.68	27.67
274	3.23	34.79	300	3.40	34.81	27.72
324	3.56	34.83	400	3.50	34.85	27.74
518	3.32	34.86	(600)	3.30	34.87	27.78

Station 4718; Apr. 16; latitude 52°28′ N., longitude 51°06′ W., depth 1,500 meters; dynamic height 1,454.608

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	0.97	33.94	0	0.97	33.94	27.21
24	0.88	33.95	25	0.85	33.95	27.23
47	1.13	34.06	50	1.20	34.09	27.32
70	1.73	34.30	75	1.95	34.35	27.48
94	2.89	34.58	100	2.85	34.58	27.58
141	2.61	34.57	150	2.60	34.59	27.61
188	2.72	34.69	200	2.80	34.71	27.69
282	3.14	34.81	300	3.15	34.82	27.75
314	3.16	-------	400	3.30	34.85	27.76
486	3.32	34.86	600	3.30	34.87	27.78
667	3.32	34.87	800	3.30	34.88	27.78
843	3.32	34.88	1,000	3.30	34.88	27.78
1,252	3,29	-------	(1,500)	3.25	34.88	27.78

Station 4719; Apr. 16; latitude 52°31′ N., longitude 50°25′ W.; depth 2,506 meters; dynamic height 1,454.574

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	2.05	34.26	0	2.05	34.26	27.40
26	2.40	34.38	25	2.40	34.38	27.46
50	2.13	34.44	50	2.15	34.44	27.53
76	2.39	34.58	75	2.40	34.58	27.62
101	2.67	34.66	100	2.65	34.66	27.67
152	3.02	34.76	150	3.00	34.76	27.72
203	3.20	34.80	200	3.20	34.80	27.73
304	3.26	34.84	300	3.25	34.84	27.75
374	3.25	34.85	400	3.30	34.85	27.76
561	3.32	34.865	600	3.30	34.87	27.78
750	3.27	34.87	800	3.30	34.87	27.78
946	3.26	34.87	1,000	3.25	34.87	27.78
1,450	3.35	34.90	(1,500)	3.35	34.90	27.79

Station 4720; Apr. 16; latitude 52°35.5′ N., longitude 49°32′ W.; depth 3,255 meters; dynamic height 1,454.603

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	3.52	34.44	0	3.52	34.44	27.41
23	3.51	34.44	25	3.50	34.44	27.41
45	2.90	34.52	50	2.90	34.55	27.56
67	2.93	34.62	75	3.00	34.64	27.62
89	3.05	34.66	100	3.00	34.66	27.64
134	2.55	34.66	150	2.65	34.68	27.68
179	2.85	34.73	200	2.95	34.76	27.72
268	3.15	34.80	300	3.15	34.81	27.74
396	3.22	34.82	400	3.25	34.82	27.74
592	3.34	34.84	600	3.35	34.84	27.74
789	3.38	34.86	800	3.40	34.86	27.76
991	3.33	34.87	1,000	3.35	34.87	27.77
1,504	3.40	34.90	1,500	3.40	34.90	27.79

STATIONS OCCUPIED IN 1952—Continued

Station 4721; Apr. 17; latitude 52°40.5′ N., longitude 48°43′ W.; depth 3,658 meters; dynamic height 1,454.736

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	5.98	34.43	0	5.98	34.43	27.12
23	5.98	34.43	25	6.00	34.43	27.12
47	5.99	34.43	50	6.00	34.44	27.13
70	5.84	34.58	75	5.75	34.58	27.27
94	5.24	34.60	100	5.20	34.60	27.36
141	4.96	34.60	150	4.95	34.60	27.38
188	4.90	34.62	200	4.85	34.63	27.42
282	4.32	34.67	300	4.20	34.68	27.53
373	3.76	34.73	400	3.70	34.75	27.64
559	3.53	34.83	600	3.55	34.84	27.72
747	3.54	34.86	800	3.55	34.86	27.74
940	3.47	34.86	1,000	3.45	34.86	27.75
1,430	3.40	34.86	(1,500)	3.40	34.86	27.76

Station 4722; Apr. 17; latitude 52°43.5′ N., longitude 47°51′ W.; depth 4,006 meters; dynamic height 1,454.731

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	5.47	34.44	0	5.47	34.44	27.20
28	5.47	34.44	25	5.45	34.44	27.20
54	5.46	34.46	50	5.45	34.45	27.21
82	5.42	34.48	75	5.45	34.47	27.23
108	5.06	34.58	100	5.20	34.56	27.33
164	4.97	34.62	150	5.00	34.61	27.39
218	4.76	34.64	200	4.85	34.64	27.43
326	3.44	34.64	300	3.70	34.64	27.55
410	3.27	34.66	400	3.30	34.66	27.61
624	3.91	34.89	600	3.90	34.88	27.72
846	3.66	34.88	800	3.75	34.88	27.73
1,062	3.54	34.89	1,000	3.55	34.89	27.76
1,629	3.40	34.90	1,500	3.45	34.90	27.78

Station 4723; Apr. 17; latitude 52°47.5′ N., longitude 46°58′ W.; depth 4,024 meters; dynamic height 1,454.707

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	7.14	34.54	0	7.14	34.54	27.05
26	6.96	34.52	25	6.95	34.52	27.07
50	7.14	34.56	50	7.15	34.56	27.07
76	6.94	34.65	75	6.95	34.65	27.17
101	6.74	34.76	100	6.75	34.76	27.29
152	5.02	34.62	150	5.05	34.62	27.39
202	4.64	34.68	200	4.65	34.67	27.48
303	4.46	34.82	300	4.35	34.81	27.62
290	4.33	34.80	400	4.20	34.87	27.69
446	4.15	34.89	600	3.95	34.92	27.75
611	3.90	34.92	800	3.70	34.90	27.76
785	3.74	34.90	1,000	3.60	34.90	27.77
1,258	3.47	34.89	(1,500)	3.40	34.89	27.78

Station 4724; Apr. 17; latitude 52°51′ N., longitude 46°09′ W.; depth 3,932, meters; dynamic height 1,454.845

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	9.53	34.93	0	9.53	34.93	26.99
28	9.55	34.95	25	9.55	34.95	27.01
56	9.39	34.99	50	9.40	34.98	27.05
83	9.42	35.04	75	9.40	35.03	27.09
110	9.40	35.06	100	9.40	35.05	27.11
166	9.71	35.12	150	9.65	35.10	27.11
222	9.75	35.15	200	9.75	35.14	27.12
332	6.47	34.82	300	7.40	34.91	27.31
412	5.47	34.82	400	5.60	34.82	27.48
629	4.00	34.88	600	4.10	34.88	27.70
854	*3.84	34.89	800	3.85	34.89	27.73
1,083	3.58	34.90	1,000	3.65	34.90	27.76
1,668	3.41	34.885	1,500	3.45	34.89	27.77

Station 4725; Apr. 18; latitude 53°35′ N., longitude 46°32′ W.; depth 3,749 meters; dynamic height 1,454.655

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	4.97	34.55	0	4.97	34.55	27.34
29	4.93	34.55	25	4.95	34.55	27.34
58	4.92	34.55	50	4.95	34.55	27.34
86	4.39	34.64	75	4.55	34.62	27.45
114	4.33	34.64	100	4.35	34.64	27.48
172	4.27	34.69	150	4.30	34.67	27.52
229	3.69	34.68	200	3.95	34.69	27.56
344	3.77	34.82	300	3.75	34.78	27.65
451	3.82	34.87	400	3.80	34.85	27.71
678	3.62	34.88	600	3.75	34.88	27.73
905	*3.49	34.89	800	3.55	34.89	27.76
1,131	3.44	34.89	1,000	3.45	34.89	27.77
1,697	3.41	34.915	1,500	3.40	34.91	27.80

Station 4726; Apr. 18; latitude 53°28.5′ N., longitude 47°29′ W.; depth 3,749 meters; dynamic height 1,454.656

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	4.60	34.58	0	4.60	34.58	27.40
26	4.56	34.58	25	4.55	34.58	27.41
52	4.56	34.58	50	4.55	34.58	27.41
78	4.15	34.63	75	4.20	34.63	27.49
104	3.81	34.62	100	3.85	34.62	27.52
155	3.50	34.65	150	3.55	34.65	27.57
206	3.24	34.64	200	3.25	34.64	27.59
310	3.76	34.78	300	3.70	34.77	27.66
401	3.92	34.88	400	3.95	34.88	27.71
601	3.72	34.88	600	3.70	34.88	27.74
800	3.54	34.87	800	3.55	34.87	27.75
1,003	3.46	34.86	1,000	3.45	34.86	27.75
1,514	3.38	34.87	1,500	3.40	34.87	27.77

Station 4727; Apr. 18; latitude 53°18′ N. longitude 48°41′ W.; depth 3,660 meters; dynamic height 1,454.656

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	5.69	34.44	0	5.69	34.44	27.17
25	5.67	34.44	25	5.67	34.44	27.17
51	4.18	34.58	50	4.20	34.58	27.45
76	3.98	34.56	75	4.00	34.56	27.46
102	3.87	34.64	100	3.85	34.63	27.52
152	3.50	34.65	150	3.50	34.65	27.58
203	3.75	34.73	200	3.70	34.72	27.62
305	4.06	34.86	300	4.05	34.86	27.69
396	3.82	34.86	400	3.85	34.86	27.71
599	3.67	34.885	600	3.65	34.88	27.74
804	3.55	34.88	800	3.55	34.88	27.75
1,009	3.48	34.87	1,000	3.45	34.87	27.76
1,529	3.39	34.89	1,500	3.40	34.89	27.78

Station 4728; Apr. 19; latitude 53°11′ N., longitude 49°40′ W.; depth 3,493 meters; dynamic height 1,454.631

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, °/oo	Depth, meters	Temperature, °C	Salinity, °/oo	σ_t
0	4.77	34.41	0	4.77	34.41	27.26
25	4.53	34.43	25	4.53	34.43	27.29
50	3.99	34.51	50	3.99	34.51	27.42
75	3.82	34.52	75	3.82	34.52	27.44
100	3.81	34.61	100	3.81	34.61	27.52
150	3.43	34.66	150	3.43	34.66	27.59
199	3.21	34.67	200	3.20	34.67	27.63
299	3.57	34.80	300	3.55	34.80	27.69
341	3.51	34.80	400	3.40	34.81	27.72
520	3.28	34.85	600	3.30	34.86	27.77
705	3.33	34.86	800	3.30	34.86	27.77
893	3.32	34.86	1,000	3.30	34.86	27.77
1,383	3.30	34.86	(1,500)	3.30	34.87	27.78

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4729; Apr. 19; latitude 53°02.5′ N., longitude 50°37′ W.; depth 3,198 meters; dynamic height 1,454.619

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	0.98	33.86	0	0.98	33.86	27.15
25	1.16	33.97	25	1.16	33.97	27.23
51	1.69	34.24	50	1.70	34.23	27.39
76	1.82	34.34	75	1.80	34.33	27.47
102	2.42	34.58	100	2.35	34.47	27.54
152	3.01	34.75	150	3.00	34.55	27.55
204	3.13	34.78	200	3.10	34.77	27.72
306	3.18	34.82	300	3.15	34.82	27.75
414	3.27	34.84	400	3.30	34.84	27.75
616	3.25	34.85	600	3.25	34.85	27.76
814	3.23	34.86	800	3.25	34.86	27.77
1,022	3.23	34.86	1,000	3.25	34.86	27.77
1,549	3.35	34.89	1,500	3.35	34.89	27.78

Station 4730; Apr. 19; latitude 52°57.5′ N., longitude 51°18′ W., depth 2,103 meters; dynamic height 1,454.583

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	0.65	33.82	0	0.65	33.82	27.14
25	2.06	34.30	25	2.06	34.30	27.43
50	2.64	34.50	50	2.64	34.50	27.54
75	2.82	34.55	75	2.82	34.55	27.56
101	2.66	34.63	100	2.65	34.63	27.64
151	2.72	34.71	150	2.70	34.71	27.70
201	3.07	34.78	200	3.05	34.78	27.72
302	3.22	34.83	300	3.20	34.83	27.75
389	3.32	34.86	400	3.35	34.86	27.76
586	3.32	34.87	600	3.30	34.87	27.78
783	*3.26	34.875	800	3.25	34.87	27.78
980	3.27	34.875	1,000	3.25	34.88	27.78
1,475	3.29	34.90	1,500	3.30	34.90	27.80

Station 4731; Apr. 19; latitude 52°55.5′ N., longitude 51°55′ N.; depth 622 meters; dynamic height 1,454.670

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	−0.62	33.16	0	−0.62	33.16	26.66
24	−0.77	33.26	25	−0.75	33.27	26.67
48	−0.63	33.67	50	−0.60	33.70	27.10
72	0.08	33.93	75	0.15	33.95	27.27
96	0.37	34.05	100	0.40	34.07	27.36
144	1.25	34.26	150	1.35	34.28	27.46
191	2.01	34.45	200	2.15	34.48	27.56
287	2.83	34.68	300	2.90	34.70	27.68
328	3.03	34.75	400	3.25	34.81	27.73
514	3.37	34.86	(600)	3.35	34.87	27.77

Station 4732; Apr. 19; latitude 52°54.5′ N., longitude 52°04′ W.; depth 366 meters; dynamic height 1,454.690

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	−0.62	33.12	0	−0.62	33.12	26.63
25	−0.75	33.19	25	−0.75	33.19	26.70
51	−0.58	33.63	50	−0.60	33.61	27.03
76	0.00	33.90	75	0.00	33.90	27.24
101	0.48	34.06	100	0.45	34.05	27.33
151	1.28	34.27	150	1.25	34.27	27.47
202	1.79	34.40	200	1.75	34.40	27.53
303	2.43	34.56	300	2.40	34.56	27.61

Station 4733; Apr. 19; latitude 53°21′ N., longitude 52°25′ W.; depth 430 meters; dynamic height 1,454.613

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	−0.37	33.66	0	−0.37	33.66	27.06
26	0.98	34.03	25	1.00	34.02	27.28
51	1.12	34.13	50	1.10	34.12	27.36
77	1.22	34.20	75	1.20	34.19	27.40
102	1.42	34.32	100	1.35	34.31	27.49
155	2.32	34.56	150	2.25	34.54	27.60
206	2.84	34.69	200	2.80	34.67	27.66
308	3.27	34.82	300	3.25	34.81	27.73
391	3.32	34.84	(400)	3.30	34.84	27.75

Station 4734; Apr. 19; latitude 53°25′ N., longitude 52°06′ W.; depth 1,188 meters; dynamic height 1,454.586

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	1.26	34.11	0	1.26	34.11	27.34
25	1.32	34.14	25	1.32	34.14	27.35
50	1.65	34.28	50	1.65	34.28	27.44
75	1.71	34.32	75	1.71	34.32	27.47
101	2.22	34.52	100	2.20	34.52	27.60
150	2.92	34.74	150	2.90	34.74	27.71
201	3.08	34.80	200	3.10	34.80	27.74
302	3.25	34.845	300	3.25	34.84	27.75
380	3.25	34.85	400	3.25	34.85	27.76
579	*3.24	34.86	(600)	3.25	34.86	27.77
			(800)	3.20	34.86	27.78
			(1,000)	3.20	34.87	27.79

Station 4735; Apr. 19–20; latitude 53°28.5′ N. longitude 51°50′ W.; depth 1,920 meters; dynamic height 1,454.597

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	1.87	34.295	0	1.87	34.29	27.43
26	1.87	34.29	25	1.85	34.29	27.43
51	1.80	34.32	50	1.80	34.32	27.47
77	2.60	34.64	75	2.60	34.63	27.64
102	2.71	34.69	100	2.70	34.68	27.67
153	3.09	34.79	150	3.10	34.78	27.72
204	3.24	34.82	200	3.25	34.82	27.74
306	3.20	34.82	300	3.20	34.82	27.75
380	3.25	34.84	400	3.25	34.84	27.75
559	3.27	34.84	600	3.30	34.85	27.76
730	-----	34.855	800	3.25	34.85	27.76
930	3.23	34.85	1,000	3.25	34.85	27.76
1,463	3.35	34.89	1,500	3.35	34.89	27.78

Station 4736; Apr. 20; latitude 53°37.5′ N., longitude 51°10′ W.; depth 2,834 meters; dynamic height 1,454.586

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	1.62	34.17	0	1.62	34.17	27.36
22	1.63	34.17	25	1.65	34.19	27.37
45	1.77	34.30	50	1.85	34.33	27.46
67	2.03	34.42	75	2.30	34.49	27.56
90	2.59	34.67	100	2.70	34.70	27.69
134	2.96	34.76	150	3.05	34.78	27.72
179	3.13	34.80	200	3.15	34.82	27.75
269	3.23	34.84	300	3.25	34.84	27.75
351	3.22	34.85	400	3.25	34.85	27.76
521	3.26	34.86	600	3.30	34.86	27.77
687	------	34.865	800	3.25	34.87	27.78
879	3.25	34.87	1,000	3.25	34.88	27.78
1,391	3.32	34.89	(1,500)	3.35	34.89	27.78

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
Station 4737; Apr. 20; latitude 53°50.5′ N., longitude 50°16′ W.; depth 3,365 meters; dynamic height 1,454.615						
0	3.95	34.56	0	3.95	34.56	27.46
22	3.94	34.57	25	3.95	34.57	27.47
44	3.85	34.58	50	3.70	34.59	27.51
67	3.34	34.64	75	3.35	34.65	27.59
89	3.32	34.65	100	3.30	34.65	27.60
133	3.23	34.65	150	3.25	34.67	27.62
177	3.36	34.70	200	3.40	34.73	27.65
266	3.41	34.80	300	3.30	34.79	27.71
340	3.13	34.78	400	3.25	34.80	27.72
536	3.42	34.85	600	3.45	34.86	27.75
750	------	34.86	800	3.40	34.87	27.77
949	3.38	34.88	1,000	3.40	34.88	27.77
1,473	3.30	34.87	1,500	3.30	34.87	27.78
Station 4738; Apr. 20; latitude 53°59′ N., longitude 49°19′ W.; depth 3,676 meters; dynamic height 1,454.620						
0	4.58	34.47	0	4.58	34.47	27.32
26	4.61	34.48	25	4.60	34.48	27.32
52	3.93	34.56	50	3.95	34.56	27.46
79	3.86	34.58	75	3.90	34.58	27.48
104	3.49	34.62	100	3.55	34.62	27.55
157	3.26	34.66	150	3.30	34.66	27.61
209	3.27	34.73	200	3.25	34.72	27.66
313	3.54	34.84	300	3.50	34.83	27.72
393	*3.54	34.86	400	3.55	34.86	27.74
602	3.34	34.86	600	3.35	34.86	27.76
821	*3.30	34.87	800	3.30	34.86	27.77
1,032	3.33	34.87	1,000	3.35	34.87	27.77
1,570	3.23	34.87	1,500	3.25	34.87	27.78
Station 4739; Apr. 20; latitude 54°07′ N., longitude 48°24′ W.; depth 3,841 meters; dynamic height 1,454.654						
0	4.57	34.55	0	4.57	34.55	27.39
28	4.55	34.56	25	4.55	34.56	27.40
55	4.39	34.62	50	4.45	34.61	27.45
83	4.18	34.61	75	4.25	34.61	27.47
109	4.08	34.64	100	4.15	34.63	27.49
165	3.94	34.70	150	3.95	34.68	27.55
220	4.20	34.78	200	4.15	34.75	27.59
329	3.86	34.80	300	3.90	34.80	27.66
382	3.92	34.84	400	3.90	34.85	27.70
576	3.75	34.88	600	3.75	34.88	27.73
773	3.53	34.88	800	3.50	34.88	27.76
979	3.48	34.89	1,000	3.50	34.89	27.77
1,518	3.38	34.88	1,500	3.40	34.88	27.77
Station 4740; Apr. 20–21; latitude 54°15′ N., longitude 47°33′ W.; depth 3,749 meters; dynamic height 1,454.619						
0	4.16	34.63	0	4.16	34.62	27.49
24	4.16	34.62	25	4.15	34.62	27.49
48	4.16	34.63	50	4.15	34.63	27.49
72	3.70	34.64	75	3.65	34.64	27.55
95	3.46	34.66	100	3.45	34.66	27.59
144	3.36	34.68	150	3.35	34.69	27.62
192	3.37	34.72	200	3.35	34.73	27.65
287	3.42	34.79	300	3.45	34.80	27.70
404	3.51	34.82	400	3.50	34.82	27.72
618	3.55	34.88	600	3.55	34.88	27.75
843	3.48	34.88	800	3.50	34.88	27.76
1,060	3.40	34.875	1,000	3.40	34.88	27.77
1,612	3.14	34.90	1,500	3.25	34.89	27.79

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
Station 4741; Apr. 29; latitude 47°16′ N., longitude 49°14′ W.; depth 91 meters; dynamic height 971.042						
0	1.24	32.82	0	1.24	32.82	26.30
26	0.50	32.82	25	0.50	32.82	26.34
52	0.35	32.84	50	0.40	32.84	26.37
78	−0.50	33.22	75	−0.40	33.17	26.67
Station 4742; Apr. 29; latitude 47°22′ N., longitude 48°47′ W.: depth 139 meters; dynamic height 971.036						
0	1.23	32.87	0	1.23	32.87	26.34
25	0.33	32.88	25	0.33	32.88	26.40
49	0.25	32.88	50	0.25	32.89	26.41
74	−0.67	33.19	75	−0.70	33.20	26.71
98	−0.83	------	100	−0.85	33.35	26.82
128	−0.02	33.51				
Station 4743; Apr. 29; latitude 47°28.5′ N., longitude 48°26′ W.; depth 174 meters; dynamic height 971.030						
0	1.07	32.89	0	1.07	32.89	26.37
25	−0.07	32.88	25	−0.07	32.88	26.42
50	−0.33	32.94	50	−0.33	32.94	26.48
75	−0.99	33.21	75	−0.99	33.21	26.73
99	−0.29	33.39	100	−0.30	33.39	26.84
149	0.68	33.78	150	0.70	33.78	27.10
Station 4744; Apr. 29; latitude 47°34′ N., longitude 48°04′ W.; depth 218 meters; dynamic height 971.019						
0	0.86	32.94	0	0.86	32.94	26.43
25	−0.32	32.98	25	−0.32	32.98	26.51
50	−0.96	33.15	50	−0.96	33.15	26.68
75	−1.02	33.26	75	−1.02	33.26	26.76
100	−0.61	33.41	100	−0.61	33.41	26.87
151	0.91	------	150	0.90	33.76	27.08
201	1.51	34.13	200	1.50	34.13	27.33
Station 4745; Apr. 29; latitude 47°41.5′ N., longitude 47°32′ W.; depth 315 meters; dynamic height 970.957						
0	1.38	33.39	0	1.38	33.39	26.75
25	1.17	33.56	25	1.17	33.56	26.90
49	0.71	33.57	50	0.70	33.57	26.94
74	−0.05	33.72	75	−0.05	33.72	27.10
99	0.47	33.86	100	0.50	33.86	27.18
148	1.54	34.16	150	1.55	34.16	27.35
197	1.76	34.32	200	1.75	34.32	27.47
286	2.39	34.48	(300)	2.50	34.50	27.55

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
Station 4746; Apr. 30; latitude 47°48.5′ N., longitude 46°54′ W.; depth 646 meters; dynamic height 970.878						
0	2.44	34.14	0	2.44	34.14	27.26
22	2.33	34.20	25	2.30	34.21	27.34
43	2.33	34.24	50	2.40	34.25	27.36
65	2.64	34.28	75	2.55	34.30	27.39
86	2.44	34.33	100	2.30	34.35	27.45
129	2.21	34.40	150	2.40	34.45	27.52
173	2.61	34.54	200	2.80	34.60	27.60
259	3.16	34.72	300	3.35	34.77	27.69
350	3.54	34.83	400	3.60	34.85	27.73
532	3.58	34.88	(600)	3.60	34.88	27.75
Station 4747; Apr. 30; latitude 47°59.5′ N., longitude 46°21′ W.; depth 1,171 meters; dynamic height 970.872						
0	3.46	34.19	0	3.46	34.19	27.21
25	2.81	34.26	25	2.81	34.26	27.34
50	2.67	34.32	50	2.67	34.32	27.40
76	2.71	34.41	75	2.70	34.41	27.46
100	2.75	34.48	100	2.75	34.48	27.51
151	2.80	34.60	150	2.80	34.60	27.60
201	3.23	34.73	200	3.25	34.73	27.66
301	3.55	34.81	300	3.55	34.81	27.70
330	3.55	34.82	400	3.55	34.82	27.71
507	3.52	34.82	600	3.55	34.85	27.73
692	3.60	34.88	800	3.55	34.88	27.75
896	3.46	34.88	(1,000)	3.45	34.88	27.76
Station 4748; Apr. 30; latitude 47°55.5′ N., longitude 46°10′ W.; depth 1,060 meters; dynamic height 970.872						
0	3.31	34.06	0	3.31	34.06	27.13
26	3.05	34.12	25	3.05	34.12	27.20
51	2.97	34.15	50	3.00	34.15	27.23
77	2.50	34.40	75	2.50	34.38	27.45
102	2.74	34.52	100	2.75	34.51	27.54
152	2.90	34.63	150	2.90	34.63	27.62
203	3.28	34.73	200	3.25	34.73	27.66
305	3.67	34.84	300	3.65	34.84	27.71
415	3.68	34.85	400	3.70	34.85	27.72
614	3.54	34.85	600	3.55	34.85	27.73
821	3.46	34.87	800	3.45	34.87	27.76
1,028	3.31	34.89	1,000	3.35	34.89	27.78
Station 4749; Apr. 30; latitude 47°47′ N., longitude 45°50′ W.; depth 436 meters; dynamic height 970.892						
0	2.83	33.87	0	2.83	33.87	27.02
21	2.08	33.90	25	2.05	33.93	27.13
43	2.00	34.09	50	2.00	34.12	27.29
64	2.15	34.17	75	2.85	34.33	27.38
86	3.67	34.47	100	3.75	34.53	27.45
128	3.79	34.62	150	3.90	34.68	27.56
170	3.96	34.73	200	3.90	34.75	27.62
256	3.50	34.76	300	3.80	34.81	27.68
341	*3.88	34.85	(400)	3.90	34.87	27.72

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
Station 4750; Apr. 30; latitude 47°43′ N., longitude 45°40′ W.; depth 306 meters; dynamic height 970.898						
0	2.97	33.90	0	2.97	33.90	27.03
23	1.94	33.98	25	2.00	34.02	27.21
47	4.19	34.34	50	4.30	34.37	27.28
70	5.39	34.57	75	5.25	34.57	27.33
94	4.81	34.57	100	4.70	34.57	27.39
141	4.14	34.59	150	4.05	34.60	27.48
187	3.83	34.66	200	3.85	34.69	27.57
253	3.96	34.82				
Station 4751; Apr. 30; latitude 47°29′ N., longitude 45°04′ W.; depth 224 meters; dynamic height 970.972						
0	4.88	33.75	0	4.88	33.75	26.72
24	4.86	33.75	25	4.85	33.75	26.72
49	4.73	33.75	50	4.75	33.75	26.74
73	4.61	33.74	75	4.60	33.75	26.75
97	4.19	33.88	100	4.20	33.90	26.91
146	4.06	-------	150	4.05	34.26	27.22
194	3.88	34.58	200	3.85	34.62	27.52
Station 4752; Apr. 30; latitude 47°22′ N., longitude 45°00′ W.; depth 188 meters; dynamic height 970.960						
0	4.88	33.73	0	4.88	33.73	26.70
26	4.81	33.75	25	4.80	33.75	26.73
51	4.73	33.74	50	4.75	33.74	26.73
77	4.63	33.75	75	4.65	33.75	26.74
101	4.14	34.05	100	4.15	34.04	27.03
153	3.95	34.48	150	3.95	34.46	27.39
Station 4753; Apr. 30; latitude 47°23′ N., longitude 45°13′ W.; depth 220 meters; dynamic height 970.970						
0	4.83	33.75	0	4.83	33.75	26.72
23	4.82	33.75	25	4.80	33.75	26.73
47	4.81	33.74	50	4.80	33.75	26.73
70	4.68	33.74	75	4.65	33.74	26.74
93	4.44	33.78	100	4.35	33.85	26.85
140	3.82	34.35	150	3.80	34.41	27.36
186	3.80	34.59	200	3.80	34.65	27.55
Station 4754; Apr. 30; latitude 47°22′ N., longitude 45°35′ W.; depth 265 meters; dynamic height 970.952						
0	4.89	33.76	0	4.89	33.76	26.73
26	4.87	33.76	25	4.90	33.76	26.73
51	4.84	33.77	50	4.85	33.77	26.74
77	4.73	33.77	75	4.75	33.77	26.75
102	4.00	34.24	100	4.00	34.23	27.19
153	3.76	34.54	150	3.75	34.53	27.45
204	4.07	34.74	200	4.05	34.73	27.58

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4755; Apr. 30; latitude 47°22′ N., longitude 45°53′ W.; depth 318 meters; dynamic height 970.933

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.68	33.74	0	4.68	33.74	26.73
25	4.64	33.75	25	4.64	33.75	26.74
49	1.96	33.81	50	1.90	33.81	27.05
74	1.70	33.84	75	1.70	33.85	27.09
98	1.80	33.99	100	1.90	34.00	27.20
147	4.23	34.60	150	4.20	34.61	27.48
197	3.81	34.70	200	3.80	34.71	27.60
295	3.99	34.84	300	4.00	34.85	27.69

Station 4756; Apr. 30; latitude 47°22′ N., longitude 46°14′ W.; depth 635 meters; dynamic height 970.914

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.05	33.79	0	2.05	33.79	27.02
25	1.84	33.80	25	1.84	33.80	27.04
50	1.60	33.97	50	1.60	33.97	27.20
75	1.42	34.08	75	1.42	34.08	27.30
100	1.48	34.16	100	1.48	34.16	27.36
150	2.11	34.36	150	2.11	34.36	27.47
200	2.41	34.48	200	2.41	34.48	27.54
300	3.28	34.74	300	3.28	34.74	27.67
376	3.90	34.84	400	3.90	34.85	27.70
570	*3.76	-------	(600)	3.75	34.87	27.73

Station 4757; May 1; latitude 47°19′ N., longitude 47°06′ W.; depth 558 meters; dynamic height 970.941

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	0.27	33.02	0	0.27	33.02	26.52
25	0.23	33.38	25	0.23	33.38	26.81
51	−0.16	33.60	50	−0.15	33.59	27.00
77	0.42	33.84	75	0.40	33.82	27.16
103	0.72	33.96	100	0.70	33.95	27.24
153	2.16	34.33	150	2.10	34.30	27.42
204	2.37	34.47	200	2.30	34.46	27.54
307	2.89	34.64	300	2.90	34.63	27.62
411	3.30	34.76	400	3.25	34.75	27.68

Station 4758; May 1; latitude 47°16.5′ N., longitude 47°16′ W.; depth 330 meters; dynamic height 970.968

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	0.15	33.05	0	0.15	33.05	26.54
22	0.01	33.06	25	0.05	33.07	26.57
45	0.32	33.33	50	0.10	33.38	26.82
67	−0.55	33.51	75	−0.40	33.56	26.99
89	−0.11	33.65	100	0.15	33.72	27.09
133	0.84	34.01	150	1.30	34.15	27.36
178	2.06	34.33	200	2.25	34.40	27.49
267	2.57	34.56	(300)	2.75	34.62	27.63

Station 4759; May 1; latitude 47°11.5′ N., longitude 47°32′ W.; depth 227 meters; dynamic height 971.010

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	0.54	32.84	0	0.54	32.84	26.36
25	−0.03	33.00	25	−0.03	33.00	26.52
51	−0.85	33.17	50	−0.87	33.17	26.68
76	−0.58	33.37	75	−0.56	33.37	26.83
101	0.06	33.51	100	0.06	33.51	26.93
152	0.73	33.83	150	0.70	33.82	27.14
203	1.56	34.12	200	1.59	34.10	27.30

Station 4760; May 1; latitude 47°05.5′ N., longitude 47°49′ W.; depth 174 meters; dynamic height 971.029

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	0.67	32.81	0	0.67	32.81	26.34
21	0.31	32.88	25	0.15	32.91	26.43
42	−0.48	33.04	50	−0.70	33.12	26.64
63	−0.96	33.26	75	−0.90	33.30	26.79
84	−0.77	33.33	100	−0.55	33.38	26.84
168	0.60	33.66	150	0.35	33.58	26.96

Station 4761; May 1; latitude 46°59′ N., longitude 48°10′ W.; depth 134 meters; dynamic height 971.041

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.19	32.82	0	1.19	32.82	26.31
30	0.52	32.88	25	0.60	32.87	26.38
58	0.29	32.94	50	0.35	32.92	26.43
88	−0.95	33.26	75	−0.60	33.09	26.60
116	0.06	33.51	100	−0.45	33.39	26.85

Station 4762; May 1; latitude 46°48′ N., longitude 48°43′ W.; depth 102 meters; dynamic height 971.047

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.57	32.79	0	1.57	32.79	26.26
24	1.05	32.81	25	1.05	32.81	26.32
49	0.81	32.82	50	0.75	32.82	26.33
73	−0.54	33.08	75	−0.55	33.09	26.60

Station 4763; May 1; latitude 46°48′ N., longitude 48°05′ W.; depth 124 meters; dynamic height 971.041

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.02	32.82	0	1.02	32.82	26.33
25	0.64	32.86	25	0.64	32.86	26.37
50	0.22	32.92	50	0.22	32.92	26.44
75	−0.54	33.22	75	−0.54	33.22	26.71
100	−0.08	33.45	100	−0.08	33.45	26.88

Station 4764; May 1: latitude 46°48′ N., longitude 47°37′ W.; depth 176 meters; dynamic height 971.041

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	0.77	32.89	0	0.77	32.89	26.38
25	0.48	32.88	25	0.48	32.88	26.40
51	−0.14	32.98	50	−0.10	32.97	26.49
76	−0.87	33.22	75	−0.85	33.21	26.72
102	−0.94	33.31	100	−0.95	33.31	26.80
153	0.36	33.61	150	0.25	33.59	26.98

Station 4765; May 1–2; latitude 46°45.5′ N., longitude 47°16′ W.; depth 330 meters; dynamic height 970.973

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	0.32	33.02	0	0.32	33.02	26.52
25	0.37	33.38	25	0.37	33.38	26.80
51	0.45	33.48	50	0.45	33.47	26.87
76	1.09	33.73	75	1.10	33.73	27.03
101	0.44	33.82	100	0.45	33.82	27.15
152	1.23	34.13	150	1.20	34.12	27.35
203	1.96	34.35	200	1.90	34.34	27.47
304	2.50	34.54	300	2.45	34.54	27.58

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t

Station 4766; May 2; latitude 46°45.5′ N., longitude 47°10′ W.; depth 733 meters; dynamic height 970.927

0	0.95	33.17	0	0.95	33.17	26.60
27	1.98	33.97	25	1.95	33.92	27.13
53	1.86	34.08	50	1.85	34.07	27.26
80	1.82	34.16	75	1.80	34.14	27.32
105	1.99	34.26	100	1.95	34.24	27.39
159	2.06	34.34	150	2.00	34.32	27.45
212	2.47	34.52	200	2.35	34.48	27.54
317	3.19	34.72	300	3.10	34.69	27.65
371	3.78	34.78	400	3.80	34.80	27.67
590	3.84	34.85	600	3.85	34.85	27.70

Station 4767; May 2; latitude 46°45.5′ N., longitude 46°54′ W.; depth 1,209 meters; dynamic height 970.927

0	1.75	33.56	0	1.75	33.56	26.86
28	1.58	33.73	25	1.60	33.72	27.00
55	1.50	33.89	50	1.50	33.87	27.13
83	1.45	34.13	75	1.45	34.08	27.29
110	1.72	34.24	100	1.60	34.20	27.38
165	2.19	34.39	150	2.10	34.35	27.46
220	2.50	34.52	200	2.40	34.47	27.54
330	3.22	34.71	300	3.05	34.66	27.63
431	3.57	34.82	400	3.50	34.78	27.68
645	3.65	34.86	600	3.65	34.85	27.72
861	*3.50	34.86	800	3.55	34.86	27.74
1,078	3.37	34.87	1,000	3.40	34.87	27.77

Station 4768; May 2; latitude 46°46′ N., longitude 46°27′ W.; depth 527 meters; dynamic height 970.927

0	3.46	33.65	0	3.46	33.65	26.79
25	2.94	33.70	25	2.94	33.70	26.87
51	1.38	33.62	50	1.40	33.62	26.93
75	1.87	33.94	75	1.85	33.94	27.15
101	1.64	34.16	100	1.65	34.16	27.35
151	3.36	34.54	150	3.35	34.54	27.50
202	4.01	34.74	200	4.00	34.73	27.59
303	3.79	34.80	300	3.80	34.80	27.67
372	3.85	34.84	400	3.85	34.85	27.70
514	3.76	34.86				

Station 4769; May 2; latitude 46°46′ N., longitude 46° 10′ W.; depth 330 meters; dynamic height 970.948

0	6.20	33.85	0	6.20	33.85	26.64
25	5.85	33.98	25	5.85	33.98	26.79
50	5.83	34.00	50	5.83	34.00	26.80
75	5.65	34.00	75	5.65	34.00	26.83
101	5.41	34.47	100	5.40	34.47	27.23
151	4.76	34.63	150	4.80	34.63	27.42
202	3.62	34.60	200	3.65	34.60	27.52
302	3.73	34.82	300	3.75	34.82	27.69

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t

Station 4770; May 2; latitude 46°46.5′ N., longitude 45°46′ W.; depth 293 meters; dynamic height 970.945

0	5.64	33.77	0	5.64	33.77	26.65
25	5.12	33.80	25	5.12	33.80	26.74
50	5.01	33.82	50	5.01	33.82	26.77
76	5.10	34.23	75	5.10	34.22	27.07
101	4.69	34.36	100	4.70	34.36	27.22
151	3.98	34.54	150	4.00	34.54	27.44
202	3.78	34.66	200	3.80	34.66	27.56
252	3.78	34.72				

Station 4771; May 2; latitude 46°48′ N., longitude 45°08′ W.; depth 220 meters; dynamic height 970.956

0	5.62	33.72	0	5.62	33.72	26.62
25	4.75	33.74	25	4.75	33.74	26.73
50	4.61	33.74	50	4.61	33.74	26.74
75	4.53	33.76	75	4.53	33.76	26.76
100	4.75	34.24	100	4.75	34.24	27.12
149	3.93	34.51	150	3.95	34.51	27.42
199	3.93	34.72	200	3.95	34.72	27.59

Station 4772; May 2; latitude 46°48′ N., longitude 44°53′ W.; depth 178 meters; dynamic height 970.966

0	5.48	33.71	0	5.48	33.71	26.62
28	4.84	33.75	25	4.90	33.75	26.72
56	4.69	33.76	50	4.70	33.76	26.75
84	4.63	33.78	75	4.65	33.77	26.76
113	3.81	34.11	100	4.15	33.95	26.96
164	3.97	34.46	150	3.90	34.38	27.32

Station 4773; May 2; latitude 46°49′ N., longitude 44°48′ W.; depth 165 meters; dynamic height 970.962

0	5.44	33.70	0	5.44	33.70	26.62
25	4.83	33.77	25	4.83	33.77	26.75
50	4.74	33.77	50	4.74	33.77	26.75
75	4.61	33.77	75	4.61	33.77	26.77
101	3.77	33.98	100	3.75	33.98	27.02
151	3.83	34.38	150	3.85	34.38	27.33

Station 4774; May 2; latitude 46°44.5′ N., longitude 44°49′ W.; depth 152 meters; dynamic height 970.967

0	5.41	33.70	0	5.41	33.70	26.62
25	4.78	33.75	25	4.78	33.75	26.73
50	4.60	33.75	50	4.60	33.75	26.75
74	4.58	33.75	75	4.55	33.75	26.76
99	4.24	33.84	100	4.20	33.85	26.87
139	3.83	34.30	(150)	3.85	34.41	27.36

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4775; May 2; latitude 46°32′ N., longitude 44°47′ W.; depth 229 meters; dynamic height 970.951

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	5.10	33.73	0	5.10	33.73	26.68
25	4.74	33.76	25	4.74	33.76	26.74
50	4.67	33.77	50	4.67	33.77	26.76
75	4.21	33.88	75	4.21	33.88	26.89
100	3.64	34.09	100	3.64	34.09	27.12
149	3.96	34.51	150	3.95	34.51	27.42
199	3.93	34.64	200	3.95	34.64	27.52

Station 4776; May 2; latitude 46°25′ N., longitude 44°47′ W.; depth 650 meters; dynamic height 970.919

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	4.93	33.68	0	4.93	33.68	26.66
25	4.59	33.73	25	4.59	33.73	26.73
50	4.09	33.92	50	4.09	33.92	26.94
75	3.72	34.16	75	3.72	34.16	27.17
99	3.93	34.41	100	3.95	34.42	27.36
149	3.91	34.61	150	3.90	34.61	27.51
199	3.80	34.74	200	3.80	34.74	27.62
298	3.90	34.85	300	3.90	34.85	27.70
387	3.72	34.83	400	3.70	34.83	27.70
581	3.58	34.86	600	3.60	34.86	27.74

Station 4777; May 2–3; latitude 46°18′ N., longitude 44°45′ W.; depth 2,637 meters; dynamic height 970.915

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	4.86	33.72	0	4.86	33.72	26.70
24	4.05	33.80	25	4.05	33.81	26.85
48	3.50	33.90	50	3.50	33.91	26.99
72	3.23	34.01	75	3.25	34.03	27.10
97	3.36	34.26	100	3.40	34.28	27.29
145	3.72	34.58	150	3.70	34.60	27.52
193	3.70	34.72	200	3.70	34.73	27.62
290	3.72	34.82	300	3.75	34.83	27.69
337	3.79	34.85	400	3.75	34.87	27.73
517	3.60	34.88	600	3.60	34.88	27.75
704	3.56	34.88	800	3.50	34.88	27.76
891	3.39	34.87	1,000	3.40	34.87	27.77
1,379	3.38	34.88				

Station 4778; May 3; latitude 46°02′ N., longitude 44°39′ W.; depth 3,475 meters; dynamic height 970.977

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	9.74	34.47	0	9.74	34.47	26.60
26	9.71	34.47	25	9.70	34.47	26.61
51	10.71	34.98	50	10.70	34.98	26.83
78	10.01	34.99	75	10.15	34.99	26.93
103	8.08	34.77	100	8.35	34.78	27.06
155	6.01	34.64	150	6.15	34.65	27.28
206	3.82	34.54	200	4.00	34.55	27.45
309	4.07	34.81	300	4.05	34.80	27.64
420	3.76	34.85	400	3.80	34.85	27.71
627	3.60	34.86	600	3.65	34.86	27.73
832	3.59	34.87	800	3.60	34.87	27.75
1,046	3.38	34.86	1,000	3.40	34.86	27.76
1,586	3.36	34.88				

Station 4779; May 3; latitude 46°03′ N., longitude 45°26′ W.; depth 2,468 meters; dynamic height 971.009

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	8.20	34.14	0	8.20	34.14	26.59
26	10.56	34.78	25	10.55	34.77	26.70
52	11.45	35.10	50	11.45	35.09	26.78
78	10.85	35.11	75	10.95	35.11	26.89
104	9.24	34.92	100	9.55	34.96	27.02
155	6.21	34.61	150	6.30	34.63	27.24
206	6.62	34.88	200	6.60	34.87	27.39
310	5.02	34.80	300	5.10	34.81	27.54
396	4.36	34.84	400	4.35	34.85	27.65
595	4.12	34.91	600	4.10	34.91	27.73
794	3.64	34.88	800	3.65	34.88	27.74
998	3.53	34.89	1,000	3.55	34.89	27.76
1,518	3.36	34.89				

Station 4780; May 3; latitude 46°04.5′ N., longitude 46°10′ W.; depth 1,691 meters; dynamic height 970.947

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	4.77	33.71	0	4.77	33.71	26.70
24	5.00	33.82	25	5.00	33.82	26.77
49	5.29	33.88	50	5.25	33.87	26.78
73	2.20	33.68	75	2.15	33.68	26.93
98	1.86	34.12	100	1.85	34.15	27.32
146	3.02	34.42	150	3.10	34.44	27.45
195	3.65	34.55	200	3.70	34.56	27.49
293	4.65	34.88	300	4.65	34.89	27.65
395	*4.67	34.96	400	4.65	34.96	27.71
597	3.98	34.92	600	4.00	34.92	27.75
802	3.68	34.90	800	3.70	34.90	27.76
1,005	3.72	34.92	1,000	3.70	34.92	27.78
1,517	3.39	34.88				

Station 4781; May 3; latitude 46°07′ N., longitude 46°46′ W.; depth 1,150 meters; dynamic height 970.942

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	5.03	33.74	0	5.03	33.74	26.69
25	4.98	33.80	25	4.98	33.80	26.75
50	2.71	33.70	50	2.71	33.70	26.89
75	3.66	34.08	75	3.66	34.08	27.11
100	5.18	34.52	100	5.18	34.52	27.30
150	3.07	34.45	150	3.07	34.45	27.46
200	3.94	34.68	200	3.94	34.68	27.55
300	4.27	31.85	300	4.27	34.85	27.66
381	*4.23	34.885	400	4.20	34.89	27.70
578	3.73	34.88	600	3.75	34.88	27.73
779	3.69	34.89	800	3.70	34.89	27.75
985	3.47	-------	(1,000)	3.50	34.89	27.77

Station 4782; May 3; latitude 46°09′ N., longitude 47°20′ W.; depth 732 meters, dynamic height 970.941

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	2.02	33.46	0	2.02	33.46	26.77
25	1.31	33.62	25	1.31	33.62	26.94
50	0.94	33.70	50	0.94	33.70	27.02
75	1.18	34.00	75	1.18	34.00	27.25
101	1.33	34.08	100	1.30	34.08	27.30
151	1.76	34.26	150	1.75	34.26	27.42
201	2.08	34.37	200	2.05	34.37	27.49
302	2.93	34.64	300	2.90	34.63	27.62
401	3.55	34.81	400	3.55	34.81	27.70
597	3.70	34.85	600	3.70	34.85	27.72

STATIONS OCCUPIED IN 1952—Continued

Station 4783; May 3; latitude 46°10.5′N., longitude 47°30′ W.; depth 439 meters; dynamic height 970.958

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.85	33.36	0	1.85	33.36	26.69
25	0.66	33.56	25	0.66	33.56	26.93
50	0.78	33.64	50	0.78	33.64	26.98
74	0.84	33.72	75	0.85	33.72	27.05
99	0.90	33.92	100	0.90	33.93	27.21
149	1.81	34.21	150	1.85	34.21	27.37
198	2.06	34.40	200	2.05	34.41	27.52
297	2.74	34.58	300	2.75	34.58	27.59
396	*3.18	34.70	400	3.15	34.71	27.66

Station 4784; May 3; latitude 46°10.5′N., longitude 47°49′ W.; depth 174 meters; dynamic height 971.014

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.29	32.86	0	1.29	32.86	26.33
25	1.16	33.05	25	1.16	33.05	26.50
50	−1.07	33.24	50	−1.07	33.24	26.75
75	−1.18	33.36	75	−1.18	33.36	26.85
101	−0.39	33.55	100	−0.45	33.54	26.97
151	0.85	33.85	150	0.85	33.85	27.15

Station 4785; May 3; latitude 46°12′ N., longitude 48°03′ W.; depth 119 meters; dynamic height 971.027

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.91	32.90	0	1.91	32.90	26.32
26	0.54	33.02	25	0.55	33.02	26.50
52	0.03	33.08	50	0.05	33.08	26.58
79	−0.68	33.23	75	−0.60	33.21	26.71
105	−0.28	33.49	100	−0.40	33.43	26.88

Station 4786; May 4; latitude 46°14.5′ N., longitude 48°33′ W.; depth 92 meters; dynamic height 971.051

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.42	32.70	0	2.42	32.70	26.12
25	1.68	32.77	25	1.68	32.77	26.23
51	0.84	32.78	50	0.90	32.78	26.29
76	−0.23	33.05	75	−0.20	33.04	26.56

Station 4787; May 4; latitude 46°17′ N., longitude 49°00′ W.; depth 70 meters; dynamic height 971.063

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.61	32.60	0	2.61	32.60	26.03
21	1.78	32.63	25	1.80	32.63	26.11
42	1.35	32.63	50	1.20	32.63	26.16

Station 4788; May 4; latitude 46°07.5′ N., longitude 48°41′ W.; depth 75 meters; dynamic height 971.055

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.38	32.66	0	2.38	32.66	26.09
23	1.51	32.70	25	1.50	32.70	26.18
45	1.27	32.72	50	1.05	32.75	26.26
68	−0.02	32.99	(75)	−0.25	33.10	26.60

Station 4789; May 4; latitude 46°01′ N., longitude 48°32′ W.; depth 88 meters; dynamic height 971.047

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.91	32.78	0	1.91	32.78	26.23
24	1.44	32.79	25	1.40	32.79	26.27
47	1.00	32.83	50	0.85	32.87	26.37
71	−0.28	33.10	(75)	−0.50	33.16	26.66

Station 4790; May 4; latitude 45°49.5′ N., longitude 48°15′ W.; depth 115 meters; dynamic height 971.025

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.68	32.91	0	1.68	32.91	26.34
25	0.25	32.96	25	0.25	32.96	26.47
50	−0.68	33.27	50	−0.68	33.27	26.76
75	−0.82	33.33	75	−0.82	33.33	26.81
100	−0.87	33.54	100	−0.87	33.54	26.98

Station 4791; May 4; latitude 45°47′ N., longitude 48°11′ W.; depth 179 meters; dynamic height 971.024

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.13	32.92	0	1.13	32.92	26.39
25	−0.26	33.15	25	−0.26	33.15	26.64
51	−1.11	33.26	50	−1.10	33.26	26.76
76	−0.95	33.37	75	−0.95	33.37	26.85
102	−0.52	33.50	100	−0.55	33.49	26.93
153	0.04	33.57	150	0.00	33.56	26.97

Station 4792; May 4; latitude 45°42′ N., longitude 48°06′ W.; depth 658 meters; dynamic height 970.972

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.02	32.90	0	1.02	32.90	26.38
24	−0.19	33.24	25	−0.20	33.24	26.72
48	−0.13	33.52	50	−0.10	33.54	26.95
72	0.55	33.72	75	0.55	33.73	27.07
96	0.63	33.78	100	0.65	33.80	27.12
144	1.17	34.06	150	1.20	34.09	27.32
191	1.83	34.28	200	1.90	34.31	27.45
287	2.62	34.54	300	2.70	34.56	27.58
378	3.04	34.69	400	3.15	34.71	27.66
570	*3.44	34.82	(600)	3.45	34.83	27.72

Station 4793; May 4; latitude 45°34.5′ N., longitude 47°52′ W.; depth 1,439 meters; dynamic height 970.922

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	3.10	33.44	0	3.10	33.44	26.65
24	2.40	33.59	25	2.40	33.60	26.84
48	2.13	33.86	50	2.10	33.88	27.08
72	2.02	34.14	75	2.05	34.17	27.33
96	4.73	34.62	100	4.75	34.63	27.43
144	4.79	34.74	150	4.80	34.75	27.52
192	4.82	34.84	200	4.75	34.84	27.60
288	3.20	34.70	300	3.20	34.70	27.65
402	3.65	34.82	400	3.65	34.82	27.70
599	3.64	34.86	600	3.65	34.86	27.73
793	3.59	34.86	800	3.60	34.86	27.74
992	3.46	34.86	1,000	3.45	34.86	27.75
1,341	3.41	34.87				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4794; May 4; latitude 45°20′ N., longitude 47°23′ W.; depth 2,509 meters; dynamic height 970.961

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	4.97	33.31	0	4.97	33.31	26.36
25	3.37	33.44	25	3.37	33.44	26.63
50	3.68	33.72	50	3.68	33.72	26.82
76	4.56	34.20	75	4.55	34.19	27.10
101	5.11	34.47	100	5.10	34.47	27.27
151	5.34	34.70	150	5.35	34.70	27.42
201	4.85	34.74	200	4.85	34.74	27.51
302	4.51	34.86	300	4.50	34.86	27.64
388	4.30	34.90	400	4.30	34.90	27.69
584	4.32	34.95	600	4.30	34.95	27.73
782	*3.91	34.925	800	3.90	34.92	27.76
979	3.85	34.93	1,000	3.85	34.93	27.76
1,474	3.44	-------				

Station 4795; May 4; latitude 45°24′ N., longitude 46°40′ W.; depth 3,011 meters; dynamic height 971.025

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	9.18	34.06	0	9.18	34.06	26.37
25	8.79	34.11	25	8.79	34.11	26.48
50	8.10	34.08	50	8.10	34.08	26.55
75	9.97	34.82	75	9.97	34.82	26.84
101	8.15	34.70	100	8.30	34.70	27.01
150	6.90	34.68	150	6.90	34.68	27.20
200	5.60	34.73	200	5.60	34.73	27.41
301	5.25	34.84	300	5.25	34.84	27.54
395	*5.14	34.94	400	5.15	34.94	27.63
602	4.53	34.99	600	4.55	34.99	27.74
809	4.19	34.96	800	4.20	34.96	27.76
1,015	3.79	34.92	1,000	3.80	34.92	27.77
1,538	3.50	34.94				

Station 4796; May 5; latitude 45°27′ N., longitude 46°00′ W.; depth 3,402 meters; dynamic height 971.025

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	8.11	34.07	0	8.11	34.07	26.55
25	8.48	34.20	25	8.48	34.20	26.60
49	8.24	34.24	50	8.25	34.24	26.66
74	10.13	34.95	75	10.10	34.95	26.92
98	7.91	34.67	100	7.85	34.67	27.06
147	7.07	34.72	150	7.00	34.72	27.22
196	5.81	34.68	200	5.70	34.68	27.35
294	4.75	34.74	300	4.80	34.76	27.53
336	*5.22	34.85	400	5.05	34.95	27.65
535	4.68	34.99	600	4.60	34.98	27.72
734	4.34	34.94	800	4.20	34.93	27.73
929	3.94	34.92	1,000	3.80	34.92	27.77
1,434	3.53	-------				

Station 4797; May 5; latitude 45°30′ N., longitude 45°25′ W.; depth 3,658 meters; dynamic height 971.082

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	9.75	34.04	0	9.75	34.04	26.26
25	10.24	34.64	25	10.24	34.64	26.65
50	11.57	35.11	50	11.57	35.11	26.77
75	12.31	35.38	75	12.31	35.38	26.84
100	11.73	35.26	100	11.73	35.26	26.86
150	10.73	35.17	150	10.73	35.17	26.98
200	6.54	34.57	200	6.54	34.57	27.16
300	6.36	34.87	300	6.36	34.87	27.43
411	5.89	34.98	400	5.90	34.98	27.57
618	4.75	34.97	600	4.80	34.97	27.70
825	*4.14	34.96	800	4.20	34.96	27.76
1,032	3.88	34.92	1,000	3.90	34.93	27.76
1,550	*3.28	34.91				

Station 4798; May 5; latitude 44°45.5′ N., longitude 45°23′ W.; depth 3,896 meters; dynamic height 971.204

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	14.84	35.77	0	14.84	35.77	26.62
26	14.46	35.76	25	14.45	35.76	26.70
53	14.12	35.68	50	14.20	35.70	26.70
79	13.31	35.49	75	13.40	35.52	26.73
105	13.40	35.52	100	13.40	35.52	26.73
157	13.52	35.61	150	13.50	35.60	26.77
209	12.64	35.49	200	12.90	35.51	26.83
314	10.01	35.20	300	9.90	35.24	27.17
309	*9.08	35.21	400	7.00	34.97	27.42
474	5.82	34.81	600	5.45	34.94	27.59
646	5.33	34.98	800	4.60	34.96	27.71
825	4.50	34.96	1,000	4.10	34.95	27.76
1,306	3.86	34.94				

Station 4799; May 5; latitude 44°18.5′ N., longitude 45°15′ W.; depth 4,115 meters; dynamic height 971.270

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	14.36	35.46	0	14.36	35.46	26.49
25	15.22	35.93	25	15.22	35.93	26.66
51	14.88	35.86	50	14.90	35.86	26.67
76	15.07	35.95	75	15.05	35.95	26.71
102	15.11	35.98	100	15.15	35.98	26.71
151	13.88	35.70	150	13.90	35.71	26.77
202	12.88	35.49	200	12.90	35.50	26.82
304	11.22	35.32	300	11.35	35.32	26.98
426	8.19	35.02	400	8.85	35.07	27.22
639	5.19	34.92	600	5.45	34.93	27.58
854	4.69	34.96	800	4.80	34.95	27.68
1,069	4.32	34.96	1,000	4.40	34.96	27.73
1,608	3.58	34.96				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4800; May 5; latitude 44°26.5′ N., longitude 45°54′ W.; depth 3,658 meters; dynamic height 971.133

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	11.79	34.40	0	11.79	34.40	26.18
19	11.35	34.60	25	11.75	34.72	26.44
38	13.95	35.56	50	14.00	35.58	26.65
58	14.02	35.58	75	11.75	35.13	26.76
76	11.71	35.12	100	11.70	35.25	26.86
115	11.71	35.34	150	11.50	35.29	26.93
154	11.44	35.25	200	8.85	34.83	27.03
230	5.69	34.46	300	5.90	34.65	27.31
260	7.66	34.67	400	5.10	34.78	27.51
388	5.21	34.77	600	4.40	34.90	27.68
515	4.57	34.86	800	4.15	34.92	27.73
658	4.29	34.92	1,000	3.90	34.91	27.75
1,038	3.86	34.91				

Station 4801; May 5; latitude 44°36.5′ N., longitude 46°40′ W.; depth 3,749 meters; dynamic height 970.996

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	8.34	33.68	0	8.34	33.68	26.20
28	6.92	33.74	25	7.00	33.73	26.44
55	6.59	33.92	50	6.65	33.90	26.62
84	3.48	33.98	75	4.20	33.96	26.96
111	5.21	34.38	100	4.50	34.17	27.10
167	5.21	34.68	150	5.25	34.63	27.37
223	4.86	34.74	200	4.95	34.72	27.48
334	4.56	34.86	300	4.65	34.83	27.60
404	4.35	34.88	400	4.35	34.88	27.67
632	4.19	34.94	600	4.20	34.94	27.74
877	3.94	34.93	800	4.05	34.93	27.74
1,098	3.62	34.905	1,000	3.75	34.92	27.77
1,654	3.44	34.90				

Station 4802; May 6; latitude 44°44′ N., longitude 47°18′ W.; depth 3,658 meters; dynamic height 970.972

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	5.91	33.43	0	5.91	33.43	26.34
24	5.32	33.60	25	5.30	33.60	26.55
49	5.32	33.63	50	5.30	33.63	26.57
72	4.71	33.78	75	4.55	33.81	26.80
97	3.12	34.02	100	3.00	34.03	27.13
145	2.21	34.26	150	2.30	34.29	27.40
193	4.22	34.73	200	4.20	34.74	27.58
290	3.88	34.78	300	3.90	34.79	27.65
376	4.14	34.90	400	4.10	34.90	27.72
560	3.85	34.87	600	3.85	34.88	27.72
742	3.73	34.90	800	3.70	34.90	27.76
932	3.60	34.885	1,000	3.60	34.89	27.76
1,422	3.44	34.88				

Station 4803; May 6; latitude 44°52.5′ N., longitude 48°04′ W.; depth 2,834 meters; dynamic height 970.920

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.64	33.27	0	2.64	33.27	26.56
24	0.69	33.43	25	0.70	33.44	26.83
49	1.23	33.74	50	1.25	33.75	27.04
73	1.82	34.05	75	1.90	34.03	27.22
98	3.58	34.43	100	3.70	34.45	27.40
146	4.61	34.65	150	4.60	34.66	27.47
195	4.16	34.72	200	4.15	34.73	27.57
293	4.11	34.83	300	4.10	34.84	27.67
389	4.13	34.90	400	4.10	34.90	27.72
584	3.83	34.90	600	3.80	34.90	27.75
778	3.60	34.89	800	3.60	34.89	27.76
991	3.50	34.89	1,000	3.50	34.89	27.77
1,560	3.44	34.90				

Station 4804; May 6; latitude 44°56′ N., longitude 48°32′ W.; depth 1,518 meters; dynamic height 970.904

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.91	33.38	0	2.91	33.38	26.62
24	2.46	33.44	25	2.45	33.45	26.72
49	1.57	33.99	50	1.55	34.01	27.23
73	1.79	34.22	75	1.80	34.23	27.39
97	2.00	34.32	100	2.05	34.32	27.45
146	2.43	34.44	150	2.50	34.45	27.51
195	3.13	34.64	200	3.15	34.65	27.61
292	3.25	34.74	300	3.30	34.75	27.68
338	3.55	34.83	400	3.60	34.85	27.73
513	3.62	34.86	600	3.65	34.88	27.74
690	3.66	34.90	800	3.65	34.90	27.76
880	3.58	34.90	1,000	3.55	34.90	27.77
1,385	3.44	34.90				

Station 4805; May 6; latitude 44°57′ N., longitude 48°45′W.; depth 1,371 meters; dynamic height 970.975

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.93	33.19	0	1.93	33.19	26.55
27	1.76	33.48	25	1.75	33.47	26.79
52	0.83	33.63	50	0.85	33.62	26.97
79	0.89	33.71	75	0.90	33.70	27.03
104	0.78	33.79	100	0.80	33.78	27.09
157	1.17	34.05	150	1.10	34.01	27.27
210	2.05	34.34	200	1.90	34.30	27.44
314	2.82	34.58	300	2.75	34.56	27.58
442	3.46	34.80	400	3.30	34.74	27.67
658	3.62	34.86	600	3.60	34.86	27.74
871	3.47	34.85	800	3.55	34.86	27.74
1,092	3.45	--------	1,000	3.45	34.86	27.75

Station 4806; May 6; latitude 44°58.5′ N., longitude 48°59′ W.; depth 604 meters; dynamic height 971.072

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	1.78	32.90	0	1.78	32.90	26.32
24	1.21	32.92	25	1.20	32.92	26.38
48	−0.26	33.13	50	−0.30	33.15	26.64
72	−0.74	33.26	75	−0.75	33.27	26.76
96	−0.62	33.36	100	−0.60	33.38	26.84
144	−0.01	33.57	150	0.10	33.60	26.99
193	0.77	33.86	200	0.90	33.90	27.19
289	2.00	34.31	300	2.15	34.35	27.46
391	2.95	34.61	400	3.00	34.63	27.61
583	3.45	34.78	600	3.50	34.79	27.69

Station 4807; May 6; latitude 44°59.5′ N., longitude 49°08′ W.; depth 77 meters; dynamic height 971.073

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.62	32.78	0	2.62	32.78	26.17
23	0.79	32.89	25	0.75	32.91	26.40
47	−0.16	33.16	50	−0.15	33.21	26.70
70	−0.09	-------	75	−0.05	33.56	26.97

Station 4808; May 6; latitude 44°59′ N., longitude 49°24′ W.; depth 70 meters; dynamic height 971.087

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.50	32.80	0	2.50	32.80	26.20
25	2.32	32.80	25	2.32	32.80	26.22
50	0.56	32.93	50	0.56	32.93	26.43

STATIONS OCCUPIED IN 1952—Continued

Station 4809; May 6; latitude 44°16′ N., longitude 49°29′ W.; depth 53 meters; dynamic height 971.083

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	3.09	32.83	0	3.09	32.83	26.17
26	0.96	32.94	25	1.00	32.94	26.42
46	0.64	32.97	(50)	0.60	32.98	26.47

Station 4810; May 7; latitude 44°14′ N., longitude 49°23′ W.; depth 93 meters; dynamic height 971.079

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.47	32.89	0	2.47	32.89	26.26
25	0.59	32.97	25	0.59	32.97	26.46
51	0.21	33.04	50	0.20	33.04	26.54
76	−0.31	33.24	75	−0.30	33.23	26.71

Station 4811; May 7; latitude 44°13.5′ N., longitude 49°19′ W.; depth 201 meters; dynamic height 971.082

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.46	32.87	0	2.46	32.87	26.25
25	1.01	32.97	25	1.01	32.97	26.44
49	0.35	33.03	50	0.35	33.03	26.52
74	−0.33	33.22	75	−0.35	33.22	26.70
98	−0.76	33.33	100	−0.75	33.33	26.81
147	0.13	33.66	150	0.15	33.66	27.04

Station 4812; May 7; latitude 44°12′ N., longitude 49°15′ W.; depth 713 meters; dynamic height 971.064

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.31	32.88	0	2.31	32.88	26.28
25	0.19	33.04	25	0.19	33.04	26.54
51	−0.85	33.23	50	−0.85	33.23	26.73
76	−0.43	33.47	75	−0.45	33.46	26.91
101	−0.15	33.56	100	−0.15	33.55	26.97
152	0.72	33.78	150	0.70	33.78	27.10
203	0.87	33.82	200	0.85	33.82	27.13
304	1.99	34.24	300	1.95	34.22	27.38
399	2.79	34.57	400	2.80	34.57	27.58
593	3.49	34.81	600	3.50	34.81	27.71

Station 4813; May 7; latitude 44°10′ N., longitude 49°07′ W.; depth 1,582 meters; dynamic height 971.043

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.36	32.89	0	2.36	32.89	26.27
25	0.17	33.07	25	0.17	33.07	26.56
50	−0.86	33.28	50	−0.86	33.28	26.77
75	−0.32	33.49	75	−0.32	33.49	26.92
99	0.32	33.68	100	0.35	33.68	27.04
149	0.74	33.78	150	0.75	33.78	27.10
199	1.11	33.95	200	1.10	33.95	27.22
298	2.10	34.33	300	2.15	34.34	27.45
404	2.90	34.62	400	2.85	34.61	27.61
600	3.70	34.84	600	3.70	34.84	27.71
792	3.67	34.87	800	3.70	34.87	27.74
990	3.61	34.88	1,000	3.60	34.88	27.75
1,484	3.51	34.88				

Station 4814; May 7; latitude 44°07′ N., longitude 48°52′ W.; depth 2,615 meters; dynamic height 971.016

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	2.20	32.87	0	2.20	32.87	26.27
24	0.00	33.06	25	−0.05	33.06	26.56
48	−0.79	33.28	50	−0.80	33.29	26.77
72	−0.26	33.50	75	−0.20	33.52	26.95
96	0.23	33.64	100	0.30	33.66	27.03
144	0.80	33.84	150	0.80	33.87	27.17
193	1.60	34.18	200	1.70	34.23	27.39
289	4.21	34.67	300	4.40	34.71	27.53
368	4.70	34.90	400	4.70	34.93	27.67
554	4.49	34.95	600	4.40	34.95	27.72
741	4.10	34.94	800	4.05	34.93	27.74
934	3.87	34.92	1,000	3.80	34.92	27.77
1,429	3.44	34.90				

Station 4815; May 7; latitude 43°58′ N., longitude 48°21′ W.; depth 3,475 meters; dynamic height 970.961

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.36	33.06	0	4.36	33.06	26.22
25	2.63	33.24	25	2.63	33.24	26.54
51	0.33	33.55	50	0.35	33.54	26.93
76	3.21	34.08	75	3.20	34.07	27.15
102	1.44	34.04	100	1.45	34.04	27.26
152	2.51	34.36	150	2.45	34.35	27.43
204	2.96	34.52	200	2.90	34.50	27.52
306	4.93	34.935	300	4.90	34.92	27.65
412	4.66	34.95	400	4.70	34.95	27.69
615	4.10	34.92	600	4.15	34.92	27.73
816	3.92	34.92	800	3.95	34.92	27.75
1,022	3.56	34.89	1,000	3.60	34.89	27.76
1,544	3.47	34.91				

Station 4816; May 7; latitude 43°48′ N., longitude 47°43′ W.; depth 3,841 meters; dynamic height 971.087

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	9.54	33.83	0	9.54	33.83	26.13
22	10.84	34.86	25	10.85	34.89	26.73
43	10.98	34.99	50	11.10	35.03	26.80
65	11.40	35.14	75	11.45	35.16	26.84
87	11.49	35.18	100	11.50	35.18	26.84
130	11.46	35.17	150	9.90	34.95	26.95
173	7.99	34.78	200	7.20	34.78	27.23
260	6.38	34.79	300	6.10	34.80	27.40
296	6.14	34.80	400	5.15	34.84	27.55
451	4.75	34.86	600	4.30	34.90	27.69
610	4.25	34.90	800	4.10	34.93	27.74
777	4.15	34.93	1,000	3.85	34.91	27.75
1,219	3.59	34.89				

Station 4817; May 7 latitude 43°36.5′ N., longitude 46°59′ W.; depth 4,490 meters; dynamic height 971.073

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	8.45	33.78	0	8.45	33.78	26.27
25	8.46	33.95	25	8.46	33.95	26.40
50	7.58	34.08	50	7.58	34.08	26.63
75	7.35	34.33	75	7.35	34.33	26.86
99	6.37	34.35	100	6.35	34.35	27.01
150	------	34.36	150	5.25	34.36	27.16
200	6.95	34.76	200	6.95	34.76	27.26
299	4.95	34.69	300	4.95	34.70	27.46
302	4.91	34.70	400	4.95	34.83	27.56
499	5.00	34.94	600	4.65	34.94	27.69
698	4.30	34.94	800	4.05	34.91	27.73
903	3.85	34.89	1,000	3.80	34.89	27.74
1,433	3.58	34.89				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4818; May 8; latitude 43°28′ N., longitude 46°14′ W.; depth 4,572 meters; dynamic height 971.040

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	8.78	33.52	0	8.78	33.52	26.01
24	7.98	33.65	25	7.90	33.65	26.25
48	6.74	33.75	50	6.65	33.75	26.50
71	5.43	33.69	75	4.95	33.69	26.67
95	2.17	33.72	100	2.20	33.74	26.96
142	2.36	34.04	150	2.45	34.11	27.24
190	3.34	34.43	200	3.55	34.48	27.43
285	4.68	34.79	300	4.85	34.84	27.58
316	4.95	34.88	400	4.85	34.93	27.65
486	4.70	34.94	600	4.55	34.94	27.70
663	4.42	34.94	800	4.10	34.93	27.74
849	4.00	34.93	1,000	3.75	34.92	27.77
1,349	3.53	34.90				

Station 4819; May 8; latitude 43°20.5′ N., longitude 45°33′ W.; depth 4,572 meters; dynamic height 971.174

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	15.37	35.52	0	15.37	35.52	26.30
28	15.34	35.51	25	15.35	35.52	26.30
56	15.19	35.57	50	15.25	35.55	26.36
84	14.26	35.67	75	14.60	35.65	26.58
111	13.29	35.50	100	13.70	35.58	26.72
334	4.83	34.51	150	11.65	35.28	26.89
400	5.09	34.70	200	9.35	34.99	27.07
584	5.14	34.96	300	5.60	34.58	27.29
756	4.35	34.93	400	5.10	34.70	27.45
954	4.07	34.93	600	5.10	34.96	27.65
1,467	3.70	34.93	800	4.30	34.93	27.71
			1,000	4.05	34.93	27.74

Station 4820; May 8; latitude 42°52.5′ N., longitude 45°53′ W.; depth 4,663 meters; dynamic height 971.577

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	19.10	36.31	0	19.10	36.31	26.01
26	18.16	36.02	25	18.20	36.04	26.03
52	17.12	36.28	50	17.15	36.27	26.47
78	16.87	36.32	75	16.90	36.32	26.57
104	16.75	36.29	100	16.75	36.30	26.59
156	16.58	36.26	150	16.60	36.26	26.59
208	16.56	36.26	200	16.55	36.26	26.60
311	*16.21	-------	300	16.30	36.18	26.60
415	*14.67	35.86	400	14.95	35.90	26.69
625	9.35	35.20	600	9.95	35.27	27.19
836	5.59	34.90	800	6.00	34.92	27.51
1,046	4.65	34.94	1,000	4.80	34.94	27.67
1,572	3.54	34.93				

Station 4821; May 8; latitude 42°28′ N., longitude 46°09′ W.; depth 4,572 meters; dynamic height 971.512

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	18.49	36.10	0	18.49	36.10	26.01
26	18.43	36.15	25	18.45	36.15	26.05
52	-----	36.32	50	17.35	36.30	26.44
78	17.90	36.44	75	17.85	36.43	26.42
103	17.61	36.40	100	17.65	36.40	26.45
156	16.75	36.22	150	16.85	36.24	26.51
207	15.92	36.11	200	16.00	36.12	26.62
310	14.40	35.85	300	14.55	35.88	26.76
421	12.65	35.62	400	13.00	35.66	26.92
630	8.39	35.08	600	9.00	35.16	27.26
			(800)	5.75	34.92	27.54
			(1,000)	4.80	34.97	27.70

Station 4822; May 8; latitude 42°47.5′ N., longitude 46°40′ W.; depth 4,207 meters; dynamic height 971.355

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	18.64	36.09	0	18.64	36.09	25.97
26	18.41	36.34	25	18.40	36.34	26.21
52	17.42	36.29	50	17.50	36.29	26.40
78	17.11	36.28	75	17.15	36.28	26.48
104	16.52	36.17	100	16.65	36.19	26.53
157	15.14	35.95	150	15.40	35.98	26.66
208	12.84	35.49	200	13.10	35.56	26.82
312	12.55	35.56	300	12.85	35.59	26.90
278	*13.35	35.64	400	10.00	35.28	27.19
456	8.58	35.11	600	6.30	34.95	27.49
660	5.74	34.93	800	5.20	34.98	27.65
844	5.06	34.995	1,000	4.70	34.98	27.71
1,336	3.91	34.94				

Station 4823; May 9; latitude 42°58.5′ N., longitude 47°21′ W.; depth 3,731 meters; dynamic height 971.229

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	15.26	35.40	0	15.26	35.40	26.24
26	15.28	35.40	25	15.25	35.40	26.24
51	16.15	35.96	50	16.15	35.96	26.47
77	14.45	35.71	75	14.55	35.73	26.64
103	13.81	35.65	100	13.90	35.65	26.72
153	13.40	35.65	150	13.40	35.65	26.83
205	13.16	35.67	200	13.20	35.67	26.89
308	10.04	35.29	300	10.25	35.31	27.17
365	8.85	35.13	400	8.10	35.06	27.33
549	5.36	34.89	600	5.05	34.90	27.61
737	4.56	34.95	800	4.40	34.95	27.72
937	4.14	34.94	1,000	4.10	34.94	27.75
1,462	3.74	34.92				

Station 4824; May 9; latitude 43°09.5′ N., longitude 48°05′ W.; depth 3,292 meters; dynamic height 971.024

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	8.54	33.33	0	8.54	33.33	25.90
27	11.91	35.16	25	11.75	35.02	26.68
53	12.66	35.46	50	12.60	35.45	26.84
80	11.34	35.20	75	11.75	35.26	26.86
105	9.55	35.00	100	10.00	35.04	27.00
159	5.06	34.40	150	5.50	34.49	27.23
212	6.75	34.87	200	6.35	34.77	27.35
317	4.52	34.77	300	4.75	34.78	27.55
404	3.93	34.78	400	3.95	34.78	27.63
606	3.92	34.87	600	3.90	34.87	27.72
811	4.00	34.93	800	4.00	34.93	27.75
1,017	3.76	34.90	1,000	3.80	34.90	27.75
1,540	3.41	34.91				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4825; May 9; latitude 43°20′ N., longitude 48°50′ W.; depth 1,920 meters; dynamic height 970.956

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	5.12	33.16	0	5.12	33.16	26.23
24	4.11	33.32	25	4.10	33.34	26.48
50	1.80	33.70	50	1.80	33.71	26.98
74	2.02	34.07	75	2.00	34.08	27.25
99	2.70	34.24	100	2.70	34.25	27.33
148	4.15	34.60	150	4.20	34.61	27.48
198	4.33	34.73	200	4.30	34.73	27.56
297	3.11	34.67	300	3.15	34.67	27.63
393	3.40	34.76	400	3.40	34.77	27.69
588	3.68	34.84	600	3.65	34.84	27.71
781	3.61	34.86	800	3.60	34.86	27.74
979	3.54	34.86	1,000	3.55	34.86	27.74
1,483	3.45	34.88				

Station 4826; May 9; latitude 42°37.5′ N., longitude 49°01′ W.; depth 2,286 meters; dynamic height 970.985

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	4.53	33.08	0	4.53	33.08	26.22
24	5.11	33.59	25	5.10	33.60	26.58
49	2.84	33.66	50	2.70	33.67	26.87
73	0.79	33.81	75	0.80	33.82	27.13
98	1.30	33.94	100	1.30	33.95	27.20
145	1.84	34.18	150	1.90	34.20	27.36
194	2.42	34.41	200	2.50	34.43	27.49
292	3.25	34.64	300	3.30	34.65	27.60
353	3.61	34.73	400	3.60	34.76	27.66
529	3.55	34.80	600	3.65	34.82	27.70
703	3.79	34.86	800	3.75	34.87	27.73
889	3.71	34.87	1,000	3.65	34.87	27.74
1,370	3.51	34.87				

Station 4827; May 9; latitude 42°24.5′ N., longitude 48°33′ W.; depth 3,109 meters; dynamic height 971.014

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	9.21	33.17	0	9.21	33.17	25.68
27	8.48	34.46	25	8.50	34.37	26.73
53	8.38	34.70	50	8.30	34.68	26.99
81	8.98	34.96	75	8.90	34.90	27.04
107	8.17	34.86	100	8.45	34.88	27.13
161	6.73	34.72	150	7.00	34.75	27.24
215	4.86	34.54	200	5.30	34.58	27.32
322	5.89	34.96	300	5.70	34.91	27.54
257	5,15	34.74	400	5.00	34.96	27.67
408	4.96	34.96	600	4.60	34.97	27.72
576	4.67	34.98	800	3.95	34.92	27.75
755	3.95	34.92	1,000	3.90	34.91	27.75
1,265	3.79	34.89				

Station 4828; May 10; latitude 41°59.5′ N., longitude 48°02′ W.; depth 3,658 meters; dynamic height 971.026

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	8.38	32.96	0	8.38	32.96	25.63
25	5.09	33.22	25	5.09	33.22	26.28
50	3.76	33.60	50	3.76	33.60	26.72
75	4.50	33.98	75	4.50	33.98	26.94
101	4.02	34.13	100	4.05	34.13	27.11
150	4.92	34.44	150	4.90	34.44	27.26
200	3.87	34.43	200	3.85	34.43	27.37
301	5.40	34.88	300	5.40	34.88	27.55
392	4.88	34.90	400	4.85	34.91	27.64
589	4.73	35.00	600	4.70	35.00	27.73
788	4.18	34.95	800	4.10	34.95	27.76
986	3.80	34.925	1,000	3.80	34.92	27.77
1,480	3.66	34.94				

Station 4829; May 10; latitude 41°34.5′ N., longitude 47°14′ W.; depth 4,207 meters; dynamic height 971.176

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	13.86	34.63	0	13.86	34.63	25.95
25	14.49	35.57	25	14.49	35.57	26.54
50	14.14	35.61	50	14.14	35.61	26.65
75	14.63	35.84	75	14.63	35.84	26.71
99	13.76	35.68	100	13.75	35.68	26.78
149	13.34	35.68	150	13.30	35.68	26.87
199	10.29	35.10	200	10.25	35.10	27.00
298	8.40	34.95	300	8.65	35.02	27.21
284	9.18	35.08	400	7.40	35.07	27.44
443	6.86	35.08	600	5.10	34.96	27.65
612	4.96	34.96	800	4.35	34.95	27.73
787	4.37	34.95	1,000	4.15	34.95	27.75
1,265	3.86	34.94				

Station 4830; May 10; latitude 40°59′ N., longitude 48°28′ W.; depth 3,011 meters; dynamic height 971.155

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	12.95	34.69	0	12.95	34.69	26.18
27	12.10	34.78	25	12.15	34.78	26.41
54	11.62	34.81	50	11.65	34.81	26.53
81	12.87	35.45	75	12.80	35.32	26.70
108	12.79	35.50	100	12.85	35.49	26.82
163	11.88	35.40	150	12.15	35.43	26.91
217	10.45	35.25	200	10.95	35.30	27.04
325	6.45	34.80	300	7.15	34.90	27.34
417	6.32	34.96	400	6.35	34.93	27.47
621	5.08	34.98	600	5.20	34.98	27.65
823	4.49	34.96	800	4.55	34.96	27.72
1,030	4.18	34.98	1,000	4.20	34.98	27.77
1,550	3.80	34.97				

STATIONS OCCUPIED IN 1952—Continued

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
Station 4831; May 10; latitude 41°31′ N., longitude 48°54′ W.; depth 3,200 meters; dynamic height 971.008						
0	7.89	32.74	0	7.89	32.74	25.54
27	3.61	33.16	25	3.90	33.15	26.34
53	2.03	33.41	50	2.20	33.40	26.70
80	1.44	33.69	75	1.50	33.64	26.94
105	1.24	33.92	100	1.25	33.88	27.14
159	2.63	34.28	150	2.25	34.22	27.35
212	4.97	34.73	200	4.50	34.67	27.49
317	4.75	34.84	300	4.80	34.82	27.58
402	4.91	34.93	400	4.90	34.93	27.65
599	4.37	34.95	600	4.35	34.95	27.73
795	4.17	34.96	800	4.20	34.96	27.76
998	4.00	34.935	1,000	4.00	34.94	27.76
1,511	3.58	34.905				
Station 4832; May 11; latitude 42°00′ N., longitude 49°27′ W.; depth 3,011 meters; dynamic height 971.032						
0	------	33.12	0	9.00	33.12	25.67
23	6.83	33.33	25	6.70	33.37	26.20
45	5.18	34.00	50	5.40	34.10	26.94
68	6.37	34.30	75	6.05	34.32	27.03
89	5.34	34.34	100	5.15	34.36	27.17
134	4.60	34.40	150	4.35	34.40	27.29
179	3.77	34.40	200	4.00	34.48	27.39
268	4.91	34.77	300	4.90	34.80	27.55
305	4.91	34.80	400	4.60	34.84	27.61
513	4.22	34.86	600	4.40	34.92	27.70
722	4.64	35.00	800	4.50	34.98	27.73
930	4.05	34.95	1,000	3.95	34.95	27.77
1,452	3.68	34.93				
Station 4833; May 11; latitude 40°59′ N., longitude 50°15′ W.; depth 3,603 meters; dynamic height 971.698						
0	19.71	36.20	0	19.71	36.20	25.78
25	19.76	36.28	25	19.76	36.28	25.82
49	18.84	36.42	50	18.80	36.42	26.17
74	18.37	36.45	75	18.35	36.45	26.32
98	18.18	36.45	100	18.20	36.45	26.35
148	18.10	36.46	150	18.10	36.46	26.38
197	18.03	36.46	200	18.00	36.46	26.41
296	*17.82	36.43	300	17.80	36.42	26.43
307	*17.82	36.41	400	16.15	36.11	26.58
464	------	35.88	600	11.55	35.44	27.03
624	10.96	35.37	800	6.80	35.06	27.51
782	7.20	35.06	1,000	5.15	35.03	27.70
1,180	4.56	35.02				

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
Station 4834; May 11; latitude 41°30′ N., longitude 50°09′ W.; depth 3,779 meters; dynamic height 971.354						
0	20.30	36.31	0	20.30	36.31	25.69
26	19.93	36.46	25	19.95	36.46	26.90
51	18.53	36.28	50	18.60	36.28	26.12
76	17.98	36.38	75	18.00	36.38	26.35
102	15.48	35.82	100	15.60	35.84	26.50
152	15.34	36.02	150	15.40	36.02	26.69
203	14.12	35.81	200	14.20	35.82	26.79
305	12.13	35.52	300	12.20	35.53	26.98
401	10.18	35.28	400	10.15	35.29	27.17
595	4.55	34.70	600	4.55	34.70	27.51
787	4.97	34.98	800	5.00	34.98	27.68
996	4.42	34.98	1,000	4.40	34.98	27.74
1,540	3.86	34.94				
Station 4835; May 11; latitude 42°02′ N., longitude 50°13′ W.; depth 3,564 meters; dynamic height 971.048						
0	7.96	32.90	0	7.96	32.90	25.65
23	3.37	33.10	25	3.30	33.11	26.37
46	2.93	33.28	50	2.80	33.33	26.59
69	2.04	33.62	75	1.80	33.64	26.92
92	1.13	33.70	100	1.20	33.74	27.04
137	1.99	34.00	150	2.40	34.11	27.25
182	3.66	34.39	200	4.10	34.51	27.41
274	5.04	34.82	300	5.10	34.84	27.56
345	5.15	34.86	400	5.05	34.87	27.59
527	4.64	34.91	600	4.55	34.93	27.69
716	4.46	34.95	800	4.35	34.95	27.73
907	4.17	34.95	1,000	4.05	34.95	27.76
1,402	3.77	34.92				
Station 4836 May 11; latitude 42°25.5′ N., longitude 50°10′ W.; depth 1,929 meters; dynamic height 971.022						
0	3.92	32.88	0	3.92	32.88	26.14
25	0.04	33.14	25	0.04	33.14	26.63
50	0.44	33.46	50	0.44	33.46	26.86
75	−0.16	33.57	75	−0.16	33.57	26.99
99	0.40	33.72	100	0.40	33.72	27.08
148	1.46	34.02	150	1.50	34.03	27.25
198	1.72	34.20	200	1.75	34.21	27.38
297	5.87	34.98	300	5.85	34.98	27.57
369	5.52	34.96	400	5.20	34.95	27.63
555	4.35	34.88	600	4.20	34.88	27.69
743	3.98	34.89	800	3.95	34.89	27.72
938	3.82	34.90	1,000	3.75	34.90	27.75
1,441	3.51	34.88				
Station 4837; May 11–12; latitude 42°45.5′ N., longitude 50°09′ W.; depth 732 meters; dynamic height 971.088						
0	2.80	32.92	0	2.80	32.92	26.27
25	1.52	32.96	25	1.52	32.96	26.39
49	0.36	33.12	50	0.35	33.12	26.59
74	−0.21	33.22	75	−0.25	33.23	26.71
98	−0.39	33.33	100	−0.40	33.34	26.81
146	0.12	33.63	150	0.20	33.66	27.04
196	0.83	33.87	200	0.90	33.89	27.18
294	1.70	34.21	300	1.75	34.23	27.39
375	2.59	34.41	400	2.85	34.46	27.49
576	3.59	34.82	600	3.65	34.85	27.72

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4838; May 12; latitude 42°49.5′ N., longitude 50°10′ W.; depth 287 meters; dynamic height 971.100

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C.	Salinity, ‰	σ_t
0	3.46	32.86	0	3.46	32.86	26.16
24	3.09	32.87	25	3.05	32.87	26.21
49	0.83	33.06	50	0.75	33.07	26.53
73	−0.05	33.21	75	−0.15	33.22	26.70
97	−0.43	33.34	100	−0.45	33.35	26.82
146	0.03	33.55	150	0.10	33.58	26.97
194	1.01	33.90	200	1.05	33.92	27.20
243	1.30	34.02				

Station 4839; May 12; latitude 42°58′ N., longitude 50°11′ W.; depth 88 meters; dynamic height 971.099

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C.	Salinity, ‰	σ_t
0	4.27	32.75	0	4.27	32.75	26.00
21	2.78	32.89	25	2.35	32.91	26.29
43	0.81	32.98	50	0.65	33.03	26.50
64	0.42	33.18	(75)	0.30	33.32	26.76

Station 4840; May 12; latitude 43°11.5′ N., longitude 50°17′ W.; depth 68 meters; dynamic height 971.121

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C.	Salinity, ‰	σ_t
0	5.44	32.22	0	5.44	32.22	25.45
22	5.00	32.31	25	4.55	32.37	25.67
43	1.69	32.81	(50)	0.95	33.00	26.47

Station 4841; June 4; latitude 47°14′ N., longitude 49°12′ W.; depth 88 meters; dynamic height 971.071

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C.	Salinity, ‰	σ_t
0	6.70	32.70	0	6.70	32.70	25.67
26	2.83	32.70	25	2.90	32.70	26.08
52	1.78	32.71	50	1.85	32.71	26.17
73	−0.46	33.04	75	−0.55	33.07	26.59

Station 4842; June 4; latitude 47°20.5′ N., longitude 48°46′ W.; depth 123 meters; dynamic height 971.061

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C.	Salinity, ‰	σ_t
0	6.81	32.58	0	6.81	32.58	25.56
25	1.79	32.67	25	1.79	32.67	26.14
51	−0.70	32.90	50	−0.70	32.90	26.46
76	−0.98	33.19	75	−1.00	33.18	26.70
102	−0.51	33.39	100	−0.55	33.38	26.84

Station 4843; June 4; latitude 47°27′ N., longitude 48°23′ W.; depth 165 meters; dynamic height 971.069

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C.	Salinity, ‰	σ_t
0	7.45	32.68	0	7.45	32.68	25.56
25	2.63	32.69	25	2.63	32.69	26.09
51	−0.14	32.72	50	−0.10	32.72	26.29
76	−0.85	33.14	75	−0.85	33.11	26.63
101	−0.37	33.34	100	−0.40	33.33	26.80
152	0.35	33.68	150	0.35	33.67	27.04

Station 4844; June 4; latitude 47°32.5′ N., longitude 48°04′ W.; depth 212 meters; dynamic height 971.057

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	7.34	32.56	0	7.34	32.56	25.47
25	1.21	32.70	25	1.21	32.70	26.21
50	−1.01	33.10	50	−1.01	33.10	26.63
75	−1.39	33.24	75	−1.39	33.24	26.76
100	−1.39	33.36	100	−1.39	33.36	26.85
151	−0.43	33.57	150	−0.45	33.57	27.00
201	1.09	33.90	200	1.05	33.89	27.17

Station 4845; June 4; latitude 47°40′ N., longitude 47°35′ W.; depth 315 meters; dynamic height 971.013

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	7.46	32.73	0	7.46	32.73	25.60
25	3.00	33.21	25	3.00	33.21	26.49
50	0.45	33.24	50	0.45	33.24	26.70
76	−0.72	33.38	75	−0.70	33.38	26.85
101	−0.27	33.58	100	−0.30	33.57	26.99
151	0.89	33.94	150	0.85	33.93	27.21
202	1.63	34.20	200	1.60	34.19	27.37
303	2.75	34.58	300	2.70	34.57	27.59

Station 4846; June 4; latitude 47°45′ N., longitude 46°55′ N.; depth 695 meters; dynamic height 970.950

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	7.29	32.62	0	7.29	32.62	25.53
25	0.72	33.41	25	0.72	33.41	26.81
50	−0.01	33.64	50	−0.01	33.64	27.03
75	0.75	33.92	75	0.75	33.92	27.22
100	1.14	34.05	100	1.14	34.05	27.29
150	1.77	34.32	150	1.77	34.32	27.47
201	2.26	34.46	200	2.25	34.46	27.54
301	3.10	34.66	300	3.10	34.66	27.63
398	3.41	34.78	400	3.40	34.78	27.69
595	3.52	34.85	600	3.55	34.85	27.73
663	3.55	-------				

Station 4847; June 5; latitude 47°58.5′ N., longitude 46°22′ W.; depth 1,188 meters; dynamic height 970.905

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	9.20	33.61	0	9.20	33.61	26.02
24	4.73	34.18	25	4.65	34.18	27.08
48	3.23	34.28	50	3.05	34.28	27.32
71	1.54	34.26	75	1.55	34.27	27.44
95	2.06	34.37	100	2 15	34.39	27.49
143	2.47	34.52	150	2.50	34.54	27.58
191	2.79	34.64	200	2.80	34.65	27.64
286	3.15	34.73	300	3.20	34.74	27.68
378	3.41	34.79	400	3.45	34.79	27.69
568	3.59	34.82	600	3.55	34.82	27.71
761	3.48	34.86	800	3.50	34.86	27.75
964	3.44	34.87	(1.000)	3.45	34.87	27.76

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4848; June 5; latitude 47°53.5′ N., longitude 46°10′ W.; depth 1,051 meters; dynamic height 970.906

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	9.97	33.71	0	9.97	33.71	25.98
24	5.86	34.01	25	5.60	34.02	26.85
47	2.75	34.14	50	2.80	34.17	27.27
71	3.02	34.32	75	3.00	34.33	27.37
94	2.73	34.40	100	2.80	34.42	27.46
141	3.01	34.59	150	3.05	34.61	27.59
189	3.30	34.68	200	3.35	34.70	27.63
283	3.58	34.81	300	3.60	34.81	27.70
364	3.64	34.82	400	3.60	34.82	27.71
552	3.56	34.84	600	3.55	34.85	27.73
746	3.54	34.86	800	3.50	34.86	27.75
945	3.37	34.845	(1,000)	3.35	34.85	27.75

Station 4849; June 5; latitude 47°45.5′ N., longitude 45°53′ W.; depth 425 meters; dynamic height 970.957

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	11.05	33.74	0	11.05	33.74	25.81
24	8.10	33.86	25	8.05	33.86	26.39
47	6.04	33.90	50	5.75	33.91	26.75
71	3.87	33.98	75	3.85	34.02	27.05
94	4.11	34.28	100	4.20	34.34	27.26
141	4.27	34.58	150	4.25	34.61	27.47
189	3.99	34.68	200	3.95	34.70	27.57
283	3.87	34.81	300	3.85	34.82	27.68
385	3.79	34.86	400	3.80	34.86	27.72

Station 4850; June 5; latitude 47°41.5′ N., longitude 45°44′ W.; depth 304 meters; dynamic height 970.967

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	10.88	33.70	0	10.88	33.70	25.81
24	7.64	33.85	25	7.55	33.85	26.46
49	5.10	33.81	50	5.10	33.81	26.75
73	4.86	34.00	75	4.80	34.01	26.94
97	4.66	34.31	100	4.70	34.33	27.19
146	4.31	34.54	150	4.30	34.55	27.42
194	4.42	34.70	200	4.40	34.71	27.53
291	3.98	34.83	300	3.95	34.84	27.68

Station 4851; June 5; latitude 47°28.5′ N., longitude 45°14′ W.; depth 224 meters; dynamic height 970.965

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	10.88	33.73	0	10.88	33.73	25.83
25	6.30	33.72	25	6.30	33.72	26.53
50	5.54	33.78	50	5.54	33.78	26.66
75	4.05	33.89	75	4.05	33.89	26.91
100	3.75	34.20	100	3.75	34.20	27.19
150	3.78	34.48	150	3.78	34.48	27.41
200	3.95	34.70	200	3.95	34.70	27.57

Station 4852; June 5; latitude 47°23.5′ N., longitude 45°04′ W.; depth 198 meters; dynamic height 970.981

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	11.15	33.66	0	11.15	33.66	25.72
25	6.65	33.71	25	6.65	33.71	26.48
51	6.04	33.73	50	6.05	33.73	26.56
76	4.35	33.80	75	4.40	33.80	26.81
102	3.54	33.96	100	3.55	33.95	27.02
153	3.84	34.39	150	3.80	34.37	27.33

Station 4853; June 5; latitude 47°23.5′ N., longitude 45°12′ W.; depth 224 meters; dynamic height 970.962

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	10.64	33.65	0	10.64	33.65	25.81
24	6.29	33.72	25	6.20	33.72	26.5
49	5.22	33.76	50	5.20	33.76	26.7
73	4.37	33.98	75	4.35	34.00	26.97
98	4.01	34.20	100	4.00	34.22	27.19
146	3.86	34.48	150	3.85	34.50	27.42
195	3.94	34.67	200	3.95	34.69	27.56

Station 4854; June 5; latitude 47°24′ N., longitude 45°37′ W.; depth 261 meters; dynamic height 970.970

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	11.42	33.67	0	11.42	33.67	25.68
25	6.68	33.77	25	6.68	33.77	26.52
51	6.29	33.81	50	6.30	33.81	26.60
76	4.30	33.92	75	4.30	33.91	26.91
102	4.07	34.20	100	4.10	34.17	27.14
152	3.87	34.52	150	3.85	34.51	27.43
203	4.08	34.71	200	4.05	34.70	27.56
254	4.00	34.80				

Station 4855; June 5; latitude 47°23′ N., longitude 45°57′ W., depth 318 meters; dynamic height 970.969

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	11.56	33.78	0	11.56	33.78	25.75
24	7.23	33.82	25	7.15	33.82	26.49
49	5.90	33.82	50	5.85	33.82	26.67
73	5.12	33.93	75	5.10	33.95	26.86
98	5.02	34.29	100	5.00	34.30	27.14
147	4.40	34.55	150	4.35	34.56	27.42
195	3.87	34.66	200	3.85	34.67	27.56
293	3.90	34.83	300	3.90	34.84	27.69

Station 4856; June 5; latitude 47°23′ N., longitude 46°19′ W.; depth 644 meters; dynamic height 970.952

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	10.87	33.62	0	10.87	33.62	25.75
25	8.90	33.92	25	8.90	33.92	26.31
50	2.93	33.74	50	2.93	33.74	26.90
74	1.95	33.77	75	1.95	33.78	27.01
99	2.86	34.35	100	2.85	34.35	27.40
149	2.68	34.44	150	2.70	34.44	27.48
198	2.76	34.56	200	2.80	34.57	27.58
297	3.66	34.79	300	3.70	34.79	27.67
333	3.68	34.81	400	3.65	34.84	27.71
527	3.63	34.88	(600)	3.60	34.88	27.75

Station 4857; June 5; latitude 47°23′ N., longitude 46°32′ W.; depth 1,097 meters; dynamic height 970.931

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/₀₀	Depth, meters	Temperature, ° C	Salinity, °/₀₀	σ_t
0	10.23	33.55	0	10.23	33.55	25.80
25	3.13	33.44	25	3.13	33.44	26.65
50	3.51	33.94	50	3.51	33.94	27.01
75	2.48	34.16	75	2.48	34.16	27.28
100	2.78	34.37	100	2.78	34.37	27.42
150	2.67	34.50	150	2.67	34.50	27.54
200	2.98	34.65	200	2.98	34.65	27.63
300	3.41	34.77	300	3.41	34.77	27.69
389	3.52	34.82	400	3.50	34.82	27.72
581	3.56	34.83	600	3.55	34.84	27.72
776	3.56	34.86	800	3.55	34.86	27.74
972	3.51	34.86	(1,000)	3.50	34.86	27.75

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4858; June 5; latitude 47°15′ N., longitude 47°18′ W.; depth 624 meters; dynamic height 970.960

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.96	32.95	0	6.96	32.95	25.84
25	0.95	33.22	25	0.95	33.22	26.64
50	−0.33	33.59	50	−0.33	33.59	27.00
75	0.06	33.76	75	0.06	33.76	27.13
100	0.66	33.94	100	0.66	33.94	27.23
150	1.44	34.26	150	1.44	34.26	27.44
200	2.04	34.44	200	2.04	34.44	27.54
300	2.75	34.62	300	2.75	34.62	27.63
334	2.90	34.68	400	3.20	34.76	27.70
497	3.49	34.82	(600)	3.55	34.84	27.72

Station 4859; June 5; latitude 47°12.5′ N., longitude 47°25′ W.; depth 329 meters; dynamic height 970.982

Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	7.09	32.76	0	7.09	32.76	25.67
24	0.79	33.14	25	0.70	33.16	26.60
49	−0.21	33.44	50	−0.20	33.44	26.88
73	−0.37	33.59	75	−0.35	33.61	27.02
97	0.54	33.87	100	0.60	33.89	27.19
146	1.27	34.14	150	1.30	34.16	27.37
194	1.92	34.34	200	1.95	34.36	27.49
291	2.60	34.57	(300)	2.65	34.58	27.60

Station 4860; June 6; latitude 47°07′ N., longitude 47°36′ W.; depth 220 meters; dynamic height 971.026

Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.88	32.56	0	6.88	32.56	25.53
21	1.56	33.03	25	0.65	33.05	26.52
43	−0.52	33.14	50	−0.55	33.17	26.67
64	−0.52	33.26	75	−0.90	33.30	26.79
85	−1.20	33.35	100	−1.15	33.42	26.91
128	−0.50	33.61	150	0.25	33.80	27.15
170	1.06	33.97	(200)	2.25	34.21	27.34

Station 4861; June 6; latitude 47°02′ N., longitude 47°47′ W.; depth 174 meters; dynamic height 971.049

Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.38	32.65	0	6.38	32.65	25.68
25	1.94	32.71	25	1.94	32.71	26.16
50	1.61	32.88	50	1.61	32.88	26.33
75	−1.08	33.24	75	−1.08	33.24	26.75
99	−1.10	33.36	100	−1.10	33.36	26.84
150	0.27	33.75	150	0.25	33.75	27.11

Station 4862; June 6; latitude 46°52.5′ N., longitude 48°09′ W.; depth 115 meters; dynamic height 971.052

Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.18	32.67	0	6.18	32.67	25.71
25	3.06	32.76	25	3.06	32.76	26.12
50	0.43	32.90	50	0.43	32.90	26.41
74	−0.76	33.15	75	−0.75	33.15	26.66
99	−0.64	33.36	100	−0.65	33.36	26.83

Station 4863; June 6; latitude 46°48.5′ N., longitude 48°41′ W.; depth 88 meters; dynamic height 971.059

Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.47	32.69	0	6.47	32.69	25.69
26	3.34	32.73	25	3.40	32.73	26.06
51	1.10	32.78	50	1.15	32.78	26.28
77	−0.30	33.17	75	−0.25	33.14	26.64

Station 4864; June 6; latitude 46°48.5′ N., longitude 48°06′ W.; depth 110 meters; dynamic height 971.049

Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	4.48	32.67	0	4.48	32.67	25.90
25	3.56	32.79	25	3.56	32.79	26.10
50	1.07	32.87	50	1.07	32.87	26.35
74	−0.67	33.26	75	−0.70	33.27	26.76
99	−0.26	33.46	100	−0.25	33.47	26.91

Station 4865; June 6; latitude 46°50′ N., longitude 47°38′ W.; depth 169 meters; dynamic height 971.052

Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.66	32.62	0	6.66	32.62	25.62
25	2.62	32.72	25	2.62	32.72	26.12
50	−0.24	-------	50	−0.24	32.89	26.43
75	−0.69	33.18	75	−0.69	33.18	26.69
100	−0.31	33.48	100	−0.31	33.48	26.91
150	0.71	33.80	150	0.71	33.80	27.12

Station 4866; June 6; latitude 46°49′ N., longitude 47°20′ W.; depth 320 meters; dynamic height 971.010

Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.46	32.64	0	6.46	32.64	25.66
24	1.70	33.11	25	1.60	33.12	26.52
47	−0.02	33.20	50	−0.20	33.21	26.70
71	−0.99	33.42	75	−0.95	33.45	26.92
94	−0.20	33.66	100	0.00	33.70	27.08
141	1.11	33.99	150	1.20	34.02	27.27
188	1.36	34.12	200	1.50	34.17	27.37
282	2.62	34.58	(300)	2.85	34.58	27.58

Station 4867; June 6; latitude 46°48.5′ N., longitude 47°12′ W.; depth 778 meters; dynamic height 970.975

Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.80	32.78	0	6.80	32.78	25.72
23	1.76	33.20	25	1.60	33.21	26.60
45	0.49	33.33	50	0.30	33.36	26.79
68	−0.13	33.59	75	−0.05	33.65	27.04
90	0.29	33.82	100	0.45	33.89	27.20
135	1.03	34.09	150	1.25	34.16	27.38
181	1.68	34.30	200	1.85	34.35	27.48
271	2.54	34.52	300	2.80	34.59	27.59
341	3.11	34.69	400	3.40	34.77	27.69
532	3.60	34.85	(600)	3.60	34.86	27.74

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4868; June 6; latitude 46°48′ N., longitude 46°59′ W.; depth 1,207 meters; dynamic height 970.926

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	7.65	33.07	0	7.65	33.07	25.83
23	1.55	33.51	25	1.55	33.53	26.85
46	1.71	33.85	50	1.75	33.89	27.12
69	1.88	34.07	75	1.80	34.08	27.27
91	1.52	34.12	100	1.55	34.15	27.34
137	1.71	34.30	150	1.95	34.35	27.48
184	2.54	34.49	200	2.80	34.53	27.54
275	3.20	34.70	300	3.20	34.74	27.68
294	3.21	34.74	400	3.40	34.82	27.73
478	3.55	34.85	600	3.55	34.87	27.75
687	3.58	34.87	800	3.55	34.87	27.75
891	3.50	34.87	(1,000)	3.45	34.87	27.76

Station 4869; June 6; latitude 46°48′ N., longitude 46°36′ W.; depth 595 meters; dynamic height 970.939

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	8.91	33.47	0	8.91	33.47	25.96
28	8.13	33.90	25	8.25	33.85	26.35
54	4.58	34.10	50	5.15	34.07	26.95
82	4.15	34.31	75	4.25	34.26	27.19
109	3.88	34.45	100	3.95	34.41	27.35
164	3.87	34.67	150	3.90	34.62	27.52
218	3.55	34.74	200	3.60	34.72	27.63
327	3.74	34.84	300	3.70	34.82	27.70
387	3.71	34.86	400	3.70	34.86	27.73
540	3.72	34.86				

Station 4870; June 6; latitude 46°48′ N., longitude 46°15′ W.; depth 333 meters; dynamic height 970.930

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	10.42	33.71	0	10.42	33.71	25.90
24	7.16	33.75	25	7.00	33.75	26.46
48	3.52	33.85	50	3.50	33.91	26.99
73	2.93	34.15	75	2.85	34.16	27.25
97	2.54	34.29	100	2.55	34.30	27.39
146	3.41	34.59	150	3.45	34.61	27.55
194	3.92	34.77	200	3.90	34.78	27.64
291	3.90	34.88	300	3.90	34.88	27.72

Station 4871; June 7; latitude 46°48.5′ N., longitude 45°48′ W.; depth 267 meters; dynamic height 970.974

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.20	33.92	0	11.20	33.92	25.92
24	8.51	33.81	25	8.45	33.81	26.29
47	6.82	33.96	50	6.50	33.96	26.69
71	4.73	33.84	75	4.55	33.85	26.83
94	4.19	34.10	100	4.15	34.15	27.12
142	3.86	34.41	150	3.85	34.46	27.39
189	3.97	34.64	200	3.95	34.68	27.55
236	3.85	34.78				

Station 4872; June 7; latitude 46°48′ N., longitude 45°29′ W.; depth 231 meters; dynamic height 970.969

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	10.28	33.66	0	10.28	33.66	25.88
25	6.62	33.72	25	6.62	33.72	26.49
50	5.22	33.76	50	5.22	33.76	26.70
76	4.28	33.85	75	4.35	33.84	26.84
101	4.16	34.15	100	4.15	34.14	27.11
151	3.87	34.47	150	3.90	34.47	27.40
201	3.93	34.68	200	3.95	34.67	27.55

Station 4873; June 7; latitude 46°48′ N., longitude 45°08′ W.; depth 172 meters; dynamic height 970.967

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	9.76	33.69	0	9.76	33.69	25.99
26	6.32	33.71	25	6.40	33.71	26.58
52	5.48	33.74	50	5.60	33.74	26.63
78	3.85	33.92	75	4.00	33.90	26.93
104	3.47	34.14	100	3.50	34.11	27.15
157	3.71	34.38	150	3.65	34.35	27.32

Station 4874; June 7; latitude 46°48′ N., longitude 44°51′ W.; depth 133 meters; dynamic height 970.965

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	10.54	33.69	0	10.54	33.69	25.86
25	6.32	33.72	25	6.32	33.72	26.53
50	4.60	33.76	50	4.60	33.76	26.76
74	3.33	33.94	75	3.30	33.94	27.03
99	3.48	34.15	100	3.50	34.16	27.19

Station 4875; June 7; latitude 46°40.5′ N., longitude 44°48′ W.; depth 181 meters; dynamic height 970.971

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	10.51	33.67	0	10.51	33.67	25.85
24	6.33	33.74	25	6.30	33.74	26.54
48	5.60	33.79	50	5.45	33.79	26.69
71	3.52	33.94	75	3.50	33.96	27.03
95	3.44	34.05	100	3.45	34.08	27.13
143	3.46	34.40	(150)	3.45	34.47	27.44

Station 4876; June 7; latitude 46°37′ N., longitude 44°47′ W.; depth 224 meters; dynamic height 970.955

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	10.68	33.76	0	10.68	33.76	25.88
25	6.81	33.74	25	6.81	33.74	26.48
51	5.13	33.99	50	5.20	33.99	26.87
76	3.72	34.11	75	3.75	34.11	27.13
101	3.91	34.40	100	3.90	34.39	27.33
151	3.42	34.60	150	3.40	34.59	27.54
202	3.80	34.74	200	3.80	34.73	27.61

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4877; June 7; latitude 46°30′ N., longitude 44°43′ W.; depth 626 meters; dynamic height 970.965

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	11.02	33.92	0	11.02	33.92	25.96
19	------	33.92	25	8.85	33.94	26.33
39	7.21	34.07	50	6.70	34.12	26.79
58	6.13	34.15	75	3.65	34.16	27.18
78	3.59	34.16	100	3.75	34.29	27.27
116	3.88	34.40	150	3.20	34.48	27.47
155	3.20	34.50	200	3.60	34.67	27.59
233	3.80	34.77	300	3.90	34.84	27.60
360	3.97	34.86	400	3.95	34.86	27.70
532	3.94	34.86	(600)	3.95	34.86	27.70

Station 4878; June 7; latitude 46°23′ N., longitude 44°41′ W.; depth 1,701 meters; dynamic height 970.989

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	12.55	34.16	0	12.55	34.16	25.85
27	9.71	34.30	25	9.90	34.29	26.43
53	8.10	34.32	50	8.30	34.32	26.72
80	5.46	34.17	75	5.75	34.18	26.95
106	4.91	34.29	100	5.00	34.28	27.12
161	3.64	34.38	150	3.75	34.36	27.32
214	4.06	34.62	200	4.05	34.57	27.46
320	3.67	34.75	300	3.75	34.72	27.61
338	3.88	34.82	400	3.85	34.84	27.69
513	3.66	-------	600	3.60	34.86	27.74
692	3.53	34.87	800	3.50	34.88	27.76
880	3.51	34.88	1,000	3.50	34.88	27.76
1,373	3.43	34.88				

Station 4879; June 7; latitude 46°03′ N., longitude 44°41′ W.; depth 3,475 meters; dynamic height 971.091

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	13.06	34.25	0	13.06	34.25	25.82
28	13.17	35.11	25	13.15	35.04	26.41
57	12.65	35.34	50	12.75	35.29	26.69
85	12.53	35.43	75	12.55	35.41	26.82
112	10.96	35.17	100	11.75	35.30	26.89
169	8.53	34.94	150	9.20	34.98	27.09
226	8.50	35.07	200	8.50	35.02	27.23
338	5.99	34.90	300	6.80	34.94	27.42
446	5.23	34.96	400	5.50	34.94	27.59
670	4.37	34.92	600	4.60	34.94	27.69
895	3.74	34.89	800	3.95	34.89	27.72
1,120	3.60	34.89	1,000	3.65	34.89	27.75
1,682	3.42	34.895				

Station 4880; June 7; latitude 46°08.5′ N., longitude 45°24′ W.; depth 2,487 meters; dynamic height 971.043

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	10.90	33.84	0	10.90	33.84	25.91
25	10.59	34.20	25	10.59	34.20	26.24
49	8.92	34.64	50	8.95	34.64	26.86
74	9.08	34.80	75	9.05	34.80	26.97
98	7.52	34.63	100	7.55	34.63	27.06
148	7.75	34.85	150	7.75	34.85	27.21
196	6.22	34.78	200	6.20	34.78	27.37
294	5.75	34.93	300	5.70	34.93	27.55
375	4.77	34.86	400	4.70	34.86	27.62
563	4.47	34.92	600	4.35	34.91	27.70
754	3.89	34.87	800	3.85	34.87	27.72
951	3.75	34.88	1,000	3.70	34.88	27.74
1,458	3.39	34.84				

Station 4881; June 7–8; latitude 46°11′ N., longitude 46°09′ W.; depth 1,371 meters; dynamic height 970.983

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	9.79	33.76	0	9.79	33.76	26.04
26	9.59	33.92	25	9.60	33.92	26.20
51	7.54	33.82	50	7.60	33.82	26.42
78	1.33	33.71	75	1.35	33.72	27.02
103	2.67	34.15	100	2.65	34.12	27.24
155	1.90	34.28	150	1.95	34.26	27.41
206	2.27	34.44	200	2.20	34.42	27.52
309	3.71	34.75	300	3.60	34.73	27.63
341	3.99	34.82	400	4.20	34.90	27.71
525	4.34	34.96	600	4.25	34.95	27.74
720	4.00	34.92	800	3.80	34.90	27.75
914	3.57	34.88	1,000	3.50	34.88	27.76
1,181	3.47	34.87				

Station 4882; June 8; latitude 46°14′ N., longitude 46°45′ W.; depth 932 meters; dynamic height 970.969

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	8.87	33.42	0	8.87	33.42	25.93
24	7.62	33.57	25	7.55	33.57	26.24
50	2.49	33.64	50	2.50	33.64	26.86
74	1.35	33.85	75	1.35	33.85	27.12
100	1.84	34.14	100	1.85	34.15	27.32
149	2.17	34.35	150	2.15	34.35	27.46
198	2.57	34.48	200	2.60	34.48	27.52
298	4.42	34.84	300	4.40	34.84	27.63
373	4.05	34.85	400	4.00	34.85	27.69
567	3.86	34.88	600	3.85	34.88	27.72
776	3.68	34.90	(800)	3.65	34.90	27.76

Station 4883; June 8; latitude 46°15′ N., longitude 47°29′ W.; depth 535 meters; dynamic height 971.002

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.28	32.64	0	6.28	32.64	25.68
26	2.09	33.09	25	2.15	33.08	26.45
53	−1.17	33.33	50	−1.10	33.30	26.79
79	−0.50	33.61	75	−0.65	33.57	27.01
106	0.16	33.80	100	0.00	33.76	27.13
157	1.40	34.08	150	1.30	34.04	27.27
210	1.69	34.24	200	1.65	34.21	27.39
316	2.63	34 58	300	2.45	34.54	27.58
400	3.12	34.71	400	3.10	34.71	27 67
489	3.38	34.80				

Station 4884; June 8; latitude 46°14′ N., longitude 47°51′ W.; depth 169 meters; dynamic height 971.052

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	5.76	32.67	0	5.76	32.67	25.77
23	2.46	32.70	25	2.25	32.71	26.14
46	0.00	33.10	50	−0.35	33.12	26.62
68	−1.22	33.24	75	−1.25	33.27	26.78
91	−1.25	33.34	100	−1.15	33.39	26.88
137	0.07	33.67	(150)	0.55	33.79	27.12

Station 4885; June 8; latitude 46°14.5′ N., longitude 48°04′ W.; depth 115 meters; dynamic height 971.055

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	5.97	32.68	0	5.97	32.68	25.76
25	2.04	32.80	25	2.04	32.80	26.24
50	−0.59	33.06	50	−0.59	33.06	26.58
76	−0.89	33.26	75	−0.90	33.26	26.76
101	−0.54	33.37	100	−0.55	33.37	26.83

Station 4886; June 8; latitude 46°16′ N., longitude 48°32′ W.; depth 93 meters; dynamic height 971.071

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	5.98	32.68	0	5.98	32.68	25.75
28	4.83	32.72	25	5.00	32.72	25.89
55	0.00	32.92	50	0.55	32.86	26.37
82	−0.32	33.27	75	−0.30	33.18	26.67

Station 4887; June 8; latitude 46°17′ N., longitude 48°57′ W.; depth 59 meters; dynamic height 971.075

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	6.16	32.66	0	6.16	32.66	25.71
25	3.86	32.64	25	3.86	32.64	25.95
50	2.24	32.74	50	2.24	32.74	26.17

Station 4888; June 8; latitude 46°07.5′ N., longitude 48°40′ W.: depth 80 meters; dynamic height 971.080

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	6.20	32.68	0	6.20	32.68	25.72
25	5.55	32.69	25	5.55	32.69	25.80
51	2.08	32.80	50	2.10	32.79	26.22
76	−0.14	33.02	75	−0.15	33.01	26.54

Station 4889; June 8–9; latitude 46°01.5′ N., longitude 48°29′ W.; depth 84 meters; dynamic height 971.075

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	5.98	32.70	0	5.98	32.70	25.76
27	5.97	32.73	25	5.95	32.72	25.79
54	0.38	32.85	50	0.80	32.93	26.42
81	−0.31	33.03	75	−0.25	32.98	26.51

Station 4890; June 9; latitude 45°52.5′ N., longitude 48°12′ W.; depth 104 meters; dynamic height 971.050

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	6.20	32.70	0	6.20	32.70	25.73
25	2.97	32.81	25	2.97	32.81	26.17
50	−0.88	33.27	50	−0.88	33.27	26.77
75	−0.81	33.29	75	−0.81	33.29	26.77
95	−0.21	33.43	(100)	−0.05	33.47	26.90

Station 4891; June 9; latitude 45°45.5′ N., longitude 48°00′ W.; depth 176 meters; dynamic height 971.048

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	5.40	32.70	0	5.40	32.70	25.83
25	0.00	32.93	25	0.00	32.93	26.46
51	−0.04	33.12	50	−0.05	33.11	26.60
76	−1.48	33.28	75	−1.50	33.28	26.79
101	−1.42	33.36	100	−1.40	33.36	26.84
152	−0.39	33.52	150	−0.45	33.51	26.95

Station 4892; June 9; latitude 45°39′ N., longitude 47°50′ W.; depth 640 meters; dynamic height 971.009

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	5.78	32.62	0	5.78	32.62	25.72
24	1.10	33.02	25	1.05	33.03	26.49
48	0.78	33.09	50	0.60	33.10	26.56
72	−1.19	33.35	75	−1.21	33.37	26.86
96	−0.85	33.51	100	−0.75	33.54	26.98
144	1.06	34.06	150	1.20	34.10	27.33
192	1.76	34.28	200	1.80	34.30	27.45
288	2.35	34.48	300	2.45	34.50	27.55
354	2.83	34.62	400	3.15	34.70	27.65
470	3.45	34.80	(600)	3.50	34.85	27.74

Station 4893; June 9; latitude 45°33′ N., longitude 47°40′ W.; depth 1,317 meters; dynamic height 970.932

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	7.79	33.00	0	7.79	33.00	25.76
26	3.97	33.65	25	4.20	33.62	26.70
52	1.59	33.90	50	1.60	33.88	27.12
78	1.42	34.09	75	1.45	34.06	27.28
104	1.66	34.22	100	1.60	34.20	27.38
155	2.38	34.50	150	2.35	34.48	27.54
207	2.64	34.56	200	2.60	34.55	27.58
311	3.33	34.74	300	3.25	34.72	27.66
409	3.61	34.81	400	3.60	34.81	27.70
613	3.60	34.86	600	3.60	34.86	27.74
819	3.51	34.86	800	3.50	34.86	27.75
1,025	3.47	34.86	1,000	3.45	34.86	27.75

Station 4894; June 9; latitude 45°20′ N., longitude 47°20′ W.; depth 2,377 meters; dynamic height 970.945

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	7.62	32.82	0	7.62	32.82	25.64
27	2.30	33.44	25	2.65	33.41	26.67
53	−0.36	33.56	50	−0.35	33.55	26.96
79	0.22	33.79	75	0.05	33.75	27.12
105	1.44	34.15	100	1.25	34.07	27.31
159	2.68	34.43	150	2.50	34.40	27.47
211	3.07	34.57	200	3.00	34.54	27.54
316	3.87	34.80	300	3.75	34.77	27.65
360	4.11	34.86	400	4.10	34.89	27.71
540	4.01	34.92	600	3.95	34.92	27.75
720	3.82	34.92	800	3.70	34.91	27.77
910	3.59	34.90	1,000	3.55	34.90	27.77
1,402	3.44	34.90				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
Station 4895; June 9; latitude 45°20′ N., longitude 46°40′ W.; depth 2,926 meters; dynamic height 970.969						
0	9.83	33.67	0	9.83	33.67	25.96
25	8.50	33.78	25	8.50	33.78	26.26
51	5.76	34.00	50	5.80	33.99	26.80
76	4.50	34.12	75	4.50	34.11	27.05
102	4.31	34.34	100	4.35	34.34	27.24
151	3.98	34.46	150	4.00	34.45	27.37
202	3.58	34.58	200	3.55	34.58	27.51
304	3.46	34.68	300	3.45	34.68	27.60
423	3.47	34.76	400	3.45	34.75	27.66
632	3.40	34.85	600	3.40	34.84	27.74
839	3.28	34.90	800	3.30	34.89	27.79
1,048	3.26	34.915	1,000	3.25	34.91	27.81
1,566	3.08	34.91				
Station 4896; June 9; latitude 45°20′ N., longitude 45°57′ W.; depth 3,310 meters; dynamic height 970.949						
0	10.97	33.62	0	10.97	33.62	25.74
25	7.31	33.77	25	7.31	33.77	26.43
50	4.30	33.93	50	4.30	33.93	26.92
74	2.58	34.06	75	2.55	34.06	27.20
99	2.41	34.17	100	2.40	34.17	27.30
149	3.73	34.58	150	3.75	34.58	27.49
198	4.46	34.77	200	4.45	34.77	27.58
297	4.51	34.90	300	4.50	34.90	27.67
363	4.43	34.92	400	4.30	34.91	27.70
544	3.70	34.88	600	3.70	34.88	27.74
725	3.83	34.92	800	3.80	34.92	27.77
914	3.73	34.91	1,000	3.70	34.91	27.77
1,396	3.57	34.92				
Station 4897; June 10; latitude 45°20′ N., longitude 45°15′ W.; depth 3,749 meters; dynamic height 971.010						
0	11.15	33.72	0	11.15	33.72	25.78
24	9.65	33.94	25	9.60	33.94	26.21
48	7.42	33.87	50	7.25	33.87	26.51
71	6.08	34.28	75	5.50	34.27	27.06
95	1.54	33.93	100	1.55	33.95	27.18
143	3.95	34.38	150	4.20	34.43	27.33
191	4.78	34.64	200	4.85	34.68	27.46
286	5.15	34.88	300	5.15	34.90	27.60
432	4.88	34.97	400	4.95	34.96	27.67
645	3.89	34.89	600	4.00	34.90	27.73
857	3.81	34.89	800	3.80	34.89	27.74
1,073	3.64	34.90	1,000	3.70	34.89	27.75
1,614	3.50	34.91				
Station 4898; June 10; latitude 44°49.5′ N., longitude 45°15′ W.; depth 2,560 meters; dynamic height 971.065						
0	12.93	34.15	0	12.93	34.15	25.77
25	12.97	34.43	25	12.97	34.43	25.98
49	12.39	35.24	50	12.35	35.25	26.74
74	12.08	35.36	75	12.05	35.36	26.88
98	------	35.22	100	10.85	35.21	26.99
148	------	35.09	150	9.45	35.08	27.12
197	6.60	34.69	200	6.55	34.69	27.25
295	5.24	34.77	300	5.20	34.78	27.49
397	4.83	34.89	400	4.80	34.89	27.63
594	3.96	34.87	600	3.95	34.87	27.71
789	3.75	34.90	800	3.75	34.90	27.75
988	3.68	34.90	1,000	3.70	34.90	27.76
1,483	3.51	34.89				

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
Station 4899; June 10; latitude 44°25.5′ N., longitude 45°28′ W.; depth 4,115 meters; dynamic height 971.238						
0	16.00	35.42	0	16.00	35.42	26.09
25	15.99	35.42	25	15.99	35.42	26.10
50	16.13	35.87	50	16.13	35.87	26.40
75	15.01	35.72	75	15.01	35.72	26.54
100	14.22	35.68	100	14.22	35.68	26.69
150	13.92	35.70	150	13.92	35.70	26.75
201	13.00	35.54	200	13.00	35.55	26.84
301	9.32	35.05	300	9.30	35.05	27.13
346	8.78	35.08	400	7.65	35.02	27.36
511	5.49	34.86	600	4.95	34.91	27.63
671	4.68	34.94	800	4.35	34.95	27.73
849	4.26	34.955	1,000	4.00	34.94	27.76
1,311	3.52	34.89				
Station 4900; June 10; latitude 44°32′ N., longitude 46°05′ W.; depth 3,749 meters; dynamic height 971.178						
0	15.03	35.08	0	15.03	35.08	26.04
27	16.12	35.58	25	16.10	35.56	26.17
53	15.62	35.84	50	15.70	35.83	26.46
80	14.62	35.77	75	14.80	35.78	26.63
106	13.91	35.68	100	14.05	35.70	26.73
160	12.71	35.51	150	13.00	35.55	26.84
212	10.49	35.19	200	11.00	35.28	27.01
318	7.69	34.94	300	8.00	34.95	27.26
422	6.50	34.98	400	6.70	34.97	27.46
629	4.88	34.98	600	5.05	34.98	27.67
836	4.30	34.96	800	4.35	34.96	27.74
1,046	3.98	34.94	1,000	4.05	34.94	27.75
1,570	3.64	34.94				
Station 4901; June 10; latitude 44°35.5′ N., longitude 46°42′ W.; depth 3,841 meters; dynamic height 971.115						
0	11.49	33.68	0	11.49	33.68	25.68
25	11.99	34.06	25	11.99	34.06	25.88
50	12.08	35.16	50	12.08	35.16	26.73
74	12.58	35.45	75	12.55	35.45	26.85
100	12.65	35.53	100	12.65	35.53	26.89
149	6.07	34.39	150	6.10	34.39	27.08
199	7.92	34.84	200	7.90	34.84	27.18
299	7.17	34.96	300	7.15	34.96	27.39
378	6.29	34.97	400	6.00	34.96	27.54
565	4.21	34.86	600	4.15	34.86	27.68
751	4.01	34.91	800	3.95	34.91	27.74
943	3.75	34.90	1,000	3.75	34.90	27.75
1,432	3.54	34.90				
Station 4902; June 10; latitude 44°43′ N., longitude 47°19′ W.; depth 3,749 meters; dynamic height 971.102						
0	11.92	34.05	0	11.92	34.05	25.89
24	13.45	34.76	25	13.45	34.80	26.17
49	13.82	35.68	50	13.80	35.68	26.77
73	13.24	35.59	75	13.20	35.58	26.82
98	12.82	35.54	100	12.75	35.53	26.87
146	10.69	35.20	150	10.30	35.21	27.08
195	7.00	34.66	200	7.00	34.66	27.17
293	7.19	34.93	300	7.15	34.93	27.36
411	5.90	34.95	400	6.00	34.95	27.53
612	4.35	34.92	600	4.40	34.92	27.70
811	3.80	34.91	800	3.80	34.91	27.76
1,014	3.75	34.93	1,000	3.75	34.93	27.77
1,526	3.46	34.92				

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
Station 4903; June 10–11; latitude 44°46′ N., longitude 47°56′ W.; depth 3,563 meters; dynamic height 971.083						
0	11.13	33.76	0	11.13	33.76	25.80
25	11.32	33.95	25	11.32	33.95	25.92
50	8.57	34.33	50	8.57	34.33	26.68
75	8.51	34.72	75	8.51	34.72	27.00
99	7.04	34.56	100	7.05	34.56	27.09
149	7.14	34.71	150	7.15	34.71	27.19
199	4.91	34.48	200	4.90	34.48	27.29
298	5.38	34.78	300	5.40	34.78	27.47
405	5.07	34.87	400	5.10	34.87	27.58
605	3.51	34.77	600	3.50	34.77	27.68
804	3.71	34.86	800	3.80	34.86	27.72
1,004	3.59	34.89	1,000	3.60	34.89	27.76
1,504	3.34	34.90				
Station 4904; June 11; latitude 44°50.5′ N., longitude 48°30′ W.; depth 2,633 meters; dynamic height 970.967						
0	10.37	33.51	0	10.37	33.51	25.75
25	11.13	34.59	25	11.13	34.59	26.45
50	6.35	34.29	50	6.35	34.29	26.96
75	3.88	34.14	75	3.88	34.14	27.13
100	4.34	34.31	100	4.34	34.31	27.22
150	1.47	34.16	150	1.47	34.16	27 36
199	1.98	34.37	200	2.00	34.37	27.49
299	5.01	34.91	300	5.00	34.91	27.63
390	4.83	34.96	400	4.80	34.96	27.69
583	4.26	34.96	600	4.20	34.96	27.76
775	3.82	34.905	800	3.75	34.91	27.76
969	3.61	34.92	1,000	3.60	34.92	27.79
1,459	3.47	34.90				
Station 4905; June 11; latitude 44°53′ N., longitude 48°47′ W.; depth 1,939 meters; dynamic height 970.997						
0	10.72	33.71	0	10.72	33.71	25.85
23	10.58	33.70	25	10.55	33.70	25.87
45	7.46	33.93	50	6.85	33.96	26.64
68	4.80	34.04	75	4.60	34,06	27.00
91	4.20	34.12	100	4.05	34.15	27.13
135	3.67	34.30	150	3.75	34.38	27.34
180	4.27	34.57	200	4.65	34.69	27.49
271	5.54	34.96	300	5.40	34.97	27.63
347	5.14	34.98	400	4.90	34.97	27.69
537	4.38	34.95	600	4.10	34.95	27.76
739	3.81	-------	800	3.80	34.93	27.77
933	3.83	34.94	1,000	3.80	34.93	27.77
1,412	3.42	34.90				
Station 4906; June 11; latitude 44°55′ N., longitude 49°01′ W.; depth 278 meters; dynamic height 971.015						
0	6.87	32.67	0	6.87	32.67	25.63
24	5.64	32.84	25	5.60	32.85	25.92
49	0.56	33.18	50	0.45	33.19	26.65
73	−0.05	33.49	75	−0.05	33.63	27.02
98	6.84	34.65	100	6.85	34.66	27.19
146	6.31	34.75	150	6.15	34.74	27.35
195	4.27	34.59	200	4.15	34.58	27.45
268	2.82	34.54				

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
Station 4907; June 11; latitude 44°56.5′ N., longitude 49°08′ W.; depth 93 meters; dynamic height 971.022						
0	6.28	32.71	0	6.28	32.71	25.73
25	3.80	32.84	25	3.80	32.84	26.12
50	0.12	33.15	50	0.12	33.15	26.64
75	−1.04	33.32	75	−1.04	33.32	26.81
Station 4908; June 11; latitude 45°01.5′ N., longitude 49°39′ W.; depth 75 meters; dynamic height 971.047						
0	5.75	32.77	0	5.75	32.77	25.85
26	4.55	32.77	25	4.60	32.77	25.97
52	1.20	33.02	50	1.40	33.01	26.45
			(75)	0.10	33.46	26.88
Station 4909; June 11; latitude 44°13′ N., longitude 49°20′ W.; depth 75 meters; dynamic height 971.036						
0	6.02	32.81	0	6.02	32.81	25.85
25	2.63	33.00	25	2.63	33.00	26.35
51	−0.41	33.17	50	−0.40	33.16	26.66
			(75)	−1.00	33.36	26.83
Station 4910; June 11; latitude 44°12′ N., longitude 49°15′ W.; depth 119 meters; dynamic height 971.044						
0	6.20	32.79	0	6.20	32.79	25.81
24	4.87	32.89	25	4.55	32.90	26.08
47	−0.69	33.08	50	−0.75	33.11	26.63
71	−1.04	33.28	(75)	−1.10	33.32	26.81
			(100)	−1.20	33.52	26.99
Station 4911; June 11; latitude 44°10.5′ N., longitude 49°09′ W.; depth 531 meters; dynamic height 971.028						
0	6.41	32.80	0	6.41	32.80	25.79
20	1.81	33.04	25	1.10	33.07	26.51
39	−0.32	33.15	50	−0.70	33.18	26.69
59	−0.87	33.22	75	−0.95	33.30	26.79
79	−0.92	33.32	100	−0.90	33.40	26.88
118	−0.77	33.46	150	−0.10	33.64	27.03
157	0.08	33.69	200	1.65	34.06	27.27
236	2.96	34.36	(300)	3.45	34.66	27.59
			(400)	3.55	34.81	27.70
Station 4912; June 11; latitude 44°09′ N., longitude 49°04′ W.; depth 1,371 meters; dynamic height 971.028						
0	6.34	32.82	0	6.34	32.82	25.82
25	2.85	32.94	25	2.85	32.94	26.28
50	0.08	33.10	50	0.08	33.10	26.59
75	−0.84	33.20	75	−0.84	33.20	26.71
100	−0.96	33.39	100	−0.96	33.39	26.87
150	0.23	33.72	150	0.23	33.72	27.09
199	2.70	34.28	200	2.70	34.29	27.36
299	3.19	34.66	300	3.20	34.66	27.62
378	3.16	34.71	400	3.20	34.73	27.67
568	3.78	34.88	600	3.75	34.88	27.73
759	3.53	34.87	800	3.50	34.87	27.76
955	3.51	-------	1,000	3.50	34.87	27.76

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4913; June 11–12; latitude 44°07′ N., longitude 48°57′ W., depth 1,939 meters; dynamic height 971.026

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	5.90	32.67	0	5.90	32.67	25.75
25	1.82	32.66	25	1.82	32.66	26.13
50	−1.26	33.24	50	−1.26	33.24	26.75
75	−0.71	33.38	75	−0.71	33.38	26.85
99	−0.03	33.60	100	0.00	33.60	27.00
149	1.27	33.96	150	1.30	33.97	27.22
199	2.22	34.27	200	2.30	34.28	27.39
298	5.24	34.88	300	5.25	34.88	27.57
391	5.10	34.98	400	5.05	34.98	27.67
587	4.05	34.92	600	4.00	34.91	27.74
783	3.77	-------	800	3.75	34.89	27.74
983	3.61	34.87	1,000	3.60	34.87	27.75
1,493	3.43	34.87				

Station 4914; June 12; latitude 44°02′ N., longitude 48°37′ W.; depth 3,109 meters; dynamic height 971.062

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	10.38	33.42	0	10.38	33.42	25.67
25	9.43	33.37	25	9.43	33.37	25.80
52	4.76	33.37	50	5.05	33.37	26.39
77	2.95	33.53	75	3.05	33.51	26.72
103	1.63	33.76	100	1.65	33.73	27.00
154	2.35	34.03	150	2.25	34.00	27.17
206	3.55	34.31	200	3.40	34.28	27.29
309	4.54	34.76	300	4.55	34.73	27.53
388	4.55	34.92	400	4.55	34.92	27.69
581	3.96	34.89	600	3.90	34.89	27.73
772	3.75	34.86	800	3.75	34.87	27.73
965	3.65	34.88	1,000	3.65	34.88	27.74
1,447	3.45	34.89				

Station 4915; June 12; latitude 43°52′ N., longitude 47°59′ W.; depth 3,658 meters; dynamic height 970.983

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	9.50	33.29	0	9.50	33.29	25.71
27	8.06	34.34	25	8.25	34.28	26.69
53	3.42	33.56	50	4.10	33.63	26.71
80	2.04	33.89	75	2.10	33.82	27.04
106	2.09	34.10	100	2.10	34.07	27.24
160	2.26	34.27	150	2.20	34.23	27.36
213	3.18	34.51	200	2.85	34.44	27.47
319	4.43	34.84	300	4.35	34.80	27.61
416	4.41	34.90	400	4.40	34.89	27.67
617	4.25	34.95	600	4.25	34.95	27.74
814	3.83	34.90	800	3.85	34.90	27.74
1,020	3.65	34.93	1,000	3.65	34.93	27.78
1,540	3.48	34.90				

Station 4916; June 12; latitude 43°40′ N., longitude 47°15′ W.; depth 3,841 meters; dynamic height 971.128

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	13.84	34.51	0	13.84	34.51	25.86
25	14.57	35.16	25	14.57	35.16	26.21
50	12.84	35.30	50	12.84	35.30	26.68
75	13.64	35.62	75	13.64	35.62	26.76
100	12.90	35.50	100	12.90	35.50	26.82
150	12.18	35.49	150	12.18	35.49	26.96
201	10.31	35.27	200	10.40	35.27	27.11
301	7.85	35.04	300	7.85	35.04	27.35
384	5.43	34.81	400	5.35	34.82	27.51
578	4.84	34.97	600	4.80	34.97	27.70
774	4.43	34.98	800	4.35	34.98	27.75
970	3.90	34.93	1,000	3.90	34.93	27.76
1,466	3.55	34.92				

Station 4917; June 12, latitude 43°29′ N., longitude 46°32′ W.; depth 4,115 meters; dynamic height 971.057

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	12.22	33.40	0	12.22	33.40	25.33
25	10.17	33.45	25	10.17	33.45	25.74
49	7.75	33.88	50	7.75	33.89	26.45
74	6.33	34.24	75	6.25	34.25	26.95
99	5.82	34.34	100	5.80	34.34	27.08
148	4.13	34.36	150	4.15	34.37	27.29
197	5.99	34.72	200	6.00	34.73	27.36
296	5.36	34.82	300	5.30	34.82	27.52
401	4.49	34.85	400	4.50	34.85	27.63
600	4.47	34.95	600	4.45	34.95	27.72
799	4.03	34.93	800	4.00	34.93	27.75
1,000	3.77	34.92	1,000	3.75	34.92	27.77
1,503	3.48	34.92				

Station 4918; June 12; latitude 43°18.5′ N., longitude 45°53′ W.; depth 3,749 meters; dynamic height 971.208

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	13.28	33.46	0	13.28	33.46	25.16
20	15.63	35.20	25	15.62	35.22	26.02
39	14.63	35.26	50	14.00	35.25	26.40
59	13.45	35.24	75	13.45	35.40	26.63
79	13.38	35.42	100	13.15	35.41	26.70
117	12.94	35.40	150	12.40	35.39	26.83
156	12.30	35.38	200	7.40	34.57	27.05
235	5.47	34.33	300	6.75	34.62	27.18
211	6.45	34.36	400	6.35	34.82	27.39
301	6.76	34.63	600	4.90	34.96	27.68
378	6.71	34.84	(800)	4.40	34.95	27.72
456	5.09	-------	(1,000)	3.90	34.93	27.76
622	4.85	34.97				

Station 4919; June 12; latitude 43°10′ N., longitude 45°21′ W.; depth 4,663 meters; dynamic height 971.565

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	19.99	36.14	0	19.99	36.14	25.65
26	18.87	36.32	25	18.85	36.31	26.07
52	18.65	36.40	50	18.65	36.39	26.19
78	18.13	36.38	75	18.15	36.38	26.31
104	18.01	36.40	100	18.05	36.40	26.35
154	18.05	36.46	150	18.05	36.45	26.39
206	17.50	36.39	200	17.60	36.40	26.46
310	15.80	36.09	300	16.00	36.12	26.62
389	14.18	35.84	400	13.95	35.81	26.84
570	10.27	35.32	600	9.50	35.24	27.24
744	5.68	34.95	800	5.45	34.96	27.61
916	5.17	34.97	1,000	4.90	34.97	27.69
1,325	3.94	34.94				

Station 4920; June 13; latitude 42°50′ N., longitude 45°38′ W.; depth 4,627 meters; dynamic height 971.611

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	19.76	36.36	0	19.76	36.36	25.89
24	18.87	36.32	25	18.85	36.32	26.09
48	18.33	36.36	50	18.30	36.36	26.26
72	18.03	36.39	75	18.00	36.39	26.36
96	-------	36.45	100	17.80	36.45	26.45
145	17.65	36.41	150	17.65	36.41	26.46
193	17.54	36.41	200	17.50	36.41	26.50
289	16.94	36.32	300	16.85	36.31	26.57
347	16.61	36.27	400	15.35	36.13	26.78
509	-------	35.74	600	10.60	35.39	27.17
663	9.16	35.18	800	6.90	35.06	27.50
846	6.47	35.04	1,000	5.55	35.02	27.65
1,332	4.52	35.02				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4921; June 13; latitude 42°31.5′ N., longitude 45°54′ W.; depth 4,572 meters; dynamic height 971.569

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	19.49	36.31	0	19.49	36.31	25.91
25	18.41	36.31	25	18.41	36.31	26.19
51	18.23	36.32	50	18.25	36.32	26.24
76	17.67	36.31	75	17.60	36.31	26.39
102	17.40	36.30	100	17.45	36.30	26.42
152	16.92	36.25	150	16.95	36.25	26.50
202	16.76	36.26	200	16.80	36.26	26.54
304	15.87	36.10	300	15.95	36.11	26.63
482	12.79	35.63	400	14.30	35.87	26.81
720	7.08	35.01	600	10.05	35.28	27.18
955	5.07	34.98	800	6.00	34.99	27.56
1,195	4.56	35.02	1,000	4.90	34.99	27.70
1,805	3.71	34.94				

Station 4922; June 13; latitude 42°48′ N., longitude 46°48′ W.; depth 3,749 meters; dynamic height 971.039

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	11.89	33.43	0	11.89	33.43	25.42
25	10.20	34.39	25	10.20	34.39	26.46
50	12.85	35.46	50	12.85	35.46	26.80
75	11.11	35.19	75	11.11	35.19	26.92
101	8.86	34.90	100	8.90	34.91	27.08
151	8.15	34.94	150	8.15	34.94	27.22
201	6.16	34.69	200	6.20	34.69	27.30
302	5.32	34.83	300	5.30	34.82	27.52
411	5.20	34.96	400	5.20	34.96	27.64
617	4.36	34.95	600	4.40	34.95	27.72
822	3.95	34.93	800	3.95	34.93	27.75
1,028	3.77	34.93	1,000	3.75	34.93	27.77

Station 4923; June 13; latitude 42°59′ N., longitude 47°29′ W.; depth 3,658 meters; dynamic height 971.016

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	12.88	33.84	0	12.88	33.84	25.53
25	9.71	33.54	25	9.71	33.54	25.88
50	4.92	33.99	50	4.92	33.99	26.91
75	6.45	34.44	75	6.45	34.44	27.07
100	5.26	34.37	100	5.26	34.37	27.16
150	5.69	34.64	150	5.69	34.64	27.32
201	4.67	34.61	200	4.70	34.61	27.42
301	4.01	34.68	300	4.00	34.68	27.55
405	3.22	34.70	400	3.20	34.70	27.65
609	4.46	34.98	600	4.40	34.98	27.74
815	4.11	34.95	800	4.15	34.95	27.75
1,020	3.79	34.93	1,000	3.80	34.93	27.77
1,536	3.47	34.92				

Station 4924; June 13; latitude 43°09.5′ N., longitude 48°10′ W.; depth 3,658 meters; dynamic height 970.971

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	9.73	33.20	0	9.73	33.20	25.61
25	8.29	33.27	25	8.29	33.27	25.88
49	4.01	33.64	50	4.00	33.67	26.76
74	3.60	34.06	75	3.50	34.06	27.11
98	2.32	34.17	100	2.30	34.17	27.31
148	2.20	34.36	150	2.20	34.37	27.48
197	3.87	34.67	200	3.90	34.67	27.56
295	3.68	34.76	300	3.70	34.76	27.65
376	*4.29	34.88	400	4.30	34.90	27.69
573	4.08	34.92	600	4.00	34.92	27.75
775	3.71	34.91	800	3.65	34.91	27.77
973	3.58	34.90	1,000	3.55	34.90	27.77
1,475	3.47	34.92				

Station 4925; June 14; latitude 43°20′ N., longitude 48°50′ W.; depth 2,560 meters; dynamic height 970.985

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	10.66	33.41	0	10.66	33.41	25.62
25	10.50	33.41	25	10.50	33.41	25.65
49	4.36	33.64	50	4.25	33.65	26.71
74	1.74	33.84	75	1.75	33.85	27.09
99	2.79	34.22	100	2.80	34.23	27.31
148	3.77	34.59	150	3.80	34.60	27.51
197	4.34	34.75	200	4.35	34.76	27.58
296	4.62	34.88	300	4.65	34.88	27.64
397	*4.48	34.92	400	4.45	34.92	27.70
600	4.08	34.92	600	4.05	34.92	27.74
808	3.80	34.90	800	3.80	34.90	27.75
1,012	3.55	34.88	1,000	3.55	34.88	27.75
1,528	3.42	34.88				

Station 4926; June 14; latitude 42°39′ N., longitude 49°07′ W.; depth 2,377 meters; dynamic height 970.939

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	9.71	33.29	0	9.71	33.29	25.68
25	5.17	33.38	25	5.17	33.38	26.39
50	2.61	33.83	50	2.61	33.83	27.00
75	1.99	34.06	75	1.99	34.06	27.24
100	3.06	34.30	100	3.06	34.30	27.34
150	2.62	34.44	150	2.62	34.44	27.49
201	3.19	34.62	200	3.20	34.62	27.59
301	3.95	34.82	300	3.95	34.82	27.67
399	3.81	34.85	400	3.85	34.85	27.70
600	4.00	34.94	600	4.00	34.94	27.76
804	3.76	34.93	800	3.75	34.93	27.77
1,011	3.61	34.92	1,000	3.60	34.92	27.79
1,533	3.44	34.92				

Station 4927; June 14; latitude 42°20.5′ N., longitude 48°31′ W.; depth 3,292 meters; dynamic height 971.007

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	10.38	33.03	0	10.38	33.03	25.37
25	4.18	33.24	25	4.18	33.24	26.39
50	0.43	33.23	50	0.43	33.23	26.68
75	−0.23	33.47	75	−0.23	33.47	26.91
100	0.55	33.77	100	0.55	33.77	27.11
150	3.06	34.25	150	3.06	34.25	27.30
199	2.31	34.33	200	2.30	34.33	27.43
299	3.86	34.69	300	3.85	34.70	27.58
401	4.83	34.94	400	4.85	34.94	27.66
605	3.96	--------	600	3.95	34.93	27.75
810	3.87	34.93	800	3.85	34.93	27.76
1,012	3.55	34.88	1,000	3.55	34.89	27.76
1,516	3.29	34.88				

Station 4928; June 14; latitude 41°56.5′ N., longitude 47°50′ W.; depth 3,704 meters; dynamic height 971.106

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	13.95	33.64	0	13.95	33.64	25.17
24	10.58	34.18	25	10.60	34.25	26.28
47	13.42	35.50	50	13.40	35.50	26.72
71	13.00	35.53	75	12.90	35.53	26.84
95	------	35.53	100	12.55	35.52	26.90
142	------	35.08	150	9.90	35.09	27.06
189	------	35.17	200	9.35	35.13	27.18
284	5.46	34.68	300	5.50	34.71	27.41
400	5.87	34.98	400	5.85	34.98	27.57
599	4.60	34.95	600	4.60	34.95	27.70
797	4.17	34.93	800	4.15	34.93	27.73
998	3.93	34.93	1,000	3.90	34.93	27.76
1,499	3.52	34.91				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4929; June 14; latitude 41°36′ N., longitude 47°17′ W.; depth 4,150 meters; dynamic height 971.128

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	13.31	33.27	0	13.31	33.27	25.01
25	9.40	33.43	25	9.40	33.43	25.84
49	8.89	34.19	50	8.90	34.22	26.55
74	9.11	34.61	75	9.10	34.63	26.83
99	10.16	35.02	100	10.15	35.02	26.96
148	8.80	34.95	150	8.75	34.95	27.14
197	7.30	34.78	200	7.20	34.78	27.23
296	5.96	34.74	300	6.00	34.74	27.37
402	6.05	34.92	400	6.05	34.92	27.51
601	4.99	34.97	600	5.00	34.97	27.68
798	4.47	34.98	800	4.45	34.98	27.74
998	4.17	34.97	1,000	4.15	34.97	27.77
1,499	3.55	34.93				

Station 4930; June 15; latitude 41°00′ N., longitude 48°30′ W.; depth 2,926 meters; dynamic height 971.212

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	16.71	35.08	0	16.71	35.08	25.66
24	15.11	35.63	25	15.10	35.63	26.46
47	14.74	35.62	50	14.65	35.62	26.54
71	14.15	35.59	75	14.05	35.56	26.63
94	13.45	35.48	100	13.35	35.48	26.71
142	12.84	35.51	150	12.80	35.52	26.86
189	12.61	35.54	200	12.35	35.51	26.94
283	9.78	35.20	300	9.45	35.16	27.19
418	7.50	35.01	400	7.70	35.02	27.36
624	5.58	35.05	600	5.75	35.05	27.64
828	4.51	34.98	800	4.60	34.99	27.73
1,033	3.98	34.92	1,000	4.00	34.93	27.75
1,544	3.74	34.93				

Station 4931; June 15; latitude 41°32′ N., longitude 48°56′ W.; depth 3,054 meters; dynamic height 971.237

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	17.89	35.55	0	17.89	35.55	25.74
25	16.20	35.74	25	16.20	35.74	26.29
50	15.78	35.78	50	15.78	35.78	26.42
75	15.17	35.88	75	15.17	35.88	26.62
101	14.05	35.72	100	14.05	35.72	26.75
150	12.95	35.52	150	12.95	35.52	26.82
201	13.01	35.58	200	13.00	35.58	26.86
302	10.67	35.35	300	10.75	35.35	27.11
401	8.54	35.12	400	8.55	35.12	27.30
600	5.38	34.97	600	5.35	34.97	27.63
799	4.67	35.00	800	4.65	35.00	27.74
1,000	3.99	34.93	1,000	4.00	34.93	27.75
1,502	3.81	34.95				

Station 4932; June 15; latitude 42°00′ N., longitude 49°27′ W.; depth 3,292 meters; dynamic height 971.107

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	11.77	33.31	0	11.77	33.31	25.35
25	7.44	33.42	25	7.44	33.42	26.14
49	4.87	33.56	50	4.90	33.62	26.62
74	9.04	34.52	75	9.10	34.54	26.76
98	11.12	35.18	100	11.10	35.18	26.92
148	4.03	34.14	150	4.10	34.14	27.11
197	6.96	34.72	200	6.95	34.72	27.23
295	5.30	34.64	300	5.40	34.64	27.36
380	6.48	35.02	400	6.25	35.00	27.54
569	3.69	34.79	600	3.65	34.80	27.68
758	3.61	34.86	800	3.65	34.87	27.74
950	3.72	34.91	1,000	3.70	34.91	27.77
1,432	3.50	34.90				

Station 4933; June 15; latitude 41°01.5′ N., longitude 50°17′ W.; depth 4,200 meters; dynamic height 971.286

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	19.20	35.60	0	19.20	35.60	25.44
24	17.02	35.52	25	17.00	35.52	25.92
49	15.47	35.65	50	15.90	35.65	26.29
73	13.75	35.37	75	13.75	35.37	26.55
98	14.46	35.73	100	14.45	35.73	26.67
147	13.23	35.57	150	13.20	35.56	26.80
195	12.89	35.55	200	12.85	35.55	26.87
293	11.56	35.52	300	11.40	35.50	27.11
414	8.58	35.10	400	8.85	35.13	27.26
621	5.88	35.02	600	6.10	35.03	27.58
830	4.64	34.98	800	4.70	34.98	27.71
1,037	4.29	34.98	1,000	4.30	34.98	27.75
1,555	3.70	34.94				

Station 4934; June 15–16; latitude 41°30′ N., longitude 50°17′ W.; depth 3,932 meters: dynamic height 971.333

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	19.13	35.90	0	19.13	35.90	25.69
24	18.46	36.15	25	18.45	36.15	26.05
49	18.02	36.20	50	18.00	36.20	26.21
73	17.40	36.29	75	17.35	36.29	26.44
98	17.16	36.27	100	17.10	36.27	26.48
147	14.72	35.77	150	14.65	35.76	26.65
195	13.83	35.72	200	13.75	35.71	26.81
293	12.14	35.51	300	12.05	35.49	26.98
393	9.80	35.24	400	9.65	35.22	27.20
587	6.43	35.04	600	6.30	35.04	27.56
779	5.03	35.00	800	4.95	35.00	27.70
976	4.42	34.97	1,000	4.35	34.97	27.75
1,470	3.88	34.96				

Station 4935; June 16; latitude 42°03.5′ N., longitude 50°25′ W.; depth 3,292 meters; dynamic height 971.097

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	10.88	32.95	0	10.88	32.95	25.22
25	6.62	33.06	25	6.62	33.06	25.96
49	4.01	33.29	50	3.90	33.29	26.45
74	1.25	33.44	75	1.25	33.45	26.80
99	4.02	34.00	100	4.10	34.01	27.01
148	5.25	34.38	150	5.25	34.39	27.18
197	5.31	34.50	200	5.30	34.50	27.26
296	4.74	34.63	300	4.80	34.64	27.43
417	5.29	34.91	400	5.25	34.89	27.58
622	4.75	34.97	600	4.80	34.97	27.70
825	4.32	34.96	800	4.35	34.96	27.74
1,031	4.15	34.96	1,000	4.15	34.96	27.76
1,545	3.54	34.90				

Station 4936; June 16; latitude 42°24.5′ N., longitude 50°27′ W.; depth 2,350 meters; dynamic height 971.019

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	7.87	32.73	0	7.87	32.73	25.54
25	5.41	33.22	25	5.41	33.22	26.24
51	−0.37	33.53	50	−0.35	33.53	26.95
75	2.22	33.88	75	2.25	33.88	27.07
101	3.00	34.06	100	3.00	34.06	27.16
151	2.47	34.12	150	2.45	34.12	27.25
202	3.85	34.47	200	3.85	34.47	27.40
303	2.72	34.50	300	2.75	34.50	27.53
404	4.15	34.83	400	4.15	34.83	27.65
605	3.62	34.84	600	3.60	34.84	27.72
807	3.62	34.84	800	3.60	34.84	27.72
1,009	3.60	34.89	1,000	3.60	34.89	27.76
1,513	3.47	34.90				

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STATIONS OCCUPIED IN 1952—Continued

Station 4937; June 16; latitude 42°42′ N., longitude 50°25′ W.; depth 1,143 meters; dynamic height 971.064

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	8.04	32.74	0	8.04	32.74	25.52
21	6.35	32.88	25	5.60	32.92	25.98
42	2.25	33.16	50	2.00	33.24	26.59
66	1.54	33.43	75	0.85	33.44	26.82
84	0.52	33.45	100	0.40	33.52	26.92
126	0.52	33.65	150	1.05	33.78	27.08
167	1.45	33.87	200	1.65	34.01	27.23
251	1.94	34.23	300	2.60	34.45	27.50
353	3.24	34.68	400	3.60	34.77	27.67
542	3.90	34.85	600	3.80	34.85	27.71
739	3.58	34.85	800	3.60	34.86	27.74
887	3.57	34.88	(1,000)	3.55	34.89	27.76

Station 4938; June 16; latitude 42°48.5′ N., longitude 50°26′ W., depth 276 meters; dynamic height 971.044

0	9.26	32.98	0	9.26	32.98	25.52
24	3.36	33.19	25	3.25	33.19	26.44
49	0.33	33.29	50	0.30	33.29	26.73
73	−0.05	33.38	75	−0.05	33.39	26.83
98	0.02	33.52	100	0.05	33.53	26.94
146	1.08	33.78	150	1.15	33.81	27.10
195	1.63	33.99	200	1.70	34.02	27.23
244	2.66	34.32				

Station 4939; June 16; latitude 42°55.5′ N., longitude 50°24′ W.; depth 102 meters; dynamic height 971.047

0	8.75	32.95	0	8.75	32.95	25.58
25	4.31	33.15	25	4.31	33.15	26.30
50	1.87	33.23	50	1.87	33.23	26.59
75	1.39	33.39	75	1.39	33.39	26.75

Station 4940; June 16; latitude 43°18.5′ N., longitude 50°25′ W.; depth 70 meters; dynamic height 971.072

0	8.36	32.16	0	8.36	32.16	25.02
25	3.55	32.65	25	3.55	32.65	25.98
49	2.70	32.90	50	2.65	32.91	26.27

Station 4941; July 12–13; latitude 50°00.5′ N., longitude 48°59′ W.; depth 1,920 meters; dynamic height 970.844

0	8.32	32.72	0	8.32	32.72	25.46
24	3.37	34.46	25	3.30	34.49	27.47
48	2.93	34.64	50	2.95	34.65	27.63
72	2.96	34.70	75	2.95	34.70	27.67
96	3.02	34.71	100	3.05	34.71	27.67
144	3.16	34.78	150	3.15	34.78	27.71
191	3.23	34.81	200	3.25	34.82	27.74
287	3.39	34.84	300	3.35	34.84	27.74
342	3.30	34.84	400	3.30	34.84	27.75
517	3.28	34.84	600	3.30	34.84	27.75
694	3.26	34.85	800	3.25	34.85	27.76
877	3.26	34.85	1,000	3.25	34.86	27.77
1,348	3.31	34.88				

Station 4942; July 13; latitude 49°50′ N., longitude 49°32′ W.; depth 1,371 meters; dynamic height 970.863

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	7.52	32.15	0	7.52	32.15	25.13
24	2.16	34.18	25	2.15	34.21	27.35
49	2.07	34.42	50	2.10	34.43	27.52
73	2.70	34.56	75	2.70	34.57	27.59
98	2.81	34.64	100	2.80	34.65	27.64
147	2.98	34.72	150	3.00	34.72	27.69
195	3.08	34.75	200	3.10	34.75	27.70
293	3.24	34.80	300	3.25	34.80	27.72
373	3.31	34.81	400	3.30	34.82	27.74
559	3.30	34.85	600	3.30	34.85	27.76
746	3.30	34.86	800	3.30	34.85	27.76
936	3.28	34.85	1,000	3.30	34.85	27.76
1,226	3.26	34.86				

Station 4943; July 13; latitude 49°38.5′ N., longitude 50°01′ W.; depth 626 meters; dynamic height 970.981

0	9.46	32.24	0	9.46	32.24	24.91
24	1.04	33.03	25	0.95	33.04	26.50
47	−1.17	33.25	50	−1.15	33.28	26.78
71	−0.99	33.48	75	−0.90	33.51	26.97
94	−0.52	33.68	100	−0.40	33.73	27.12
141	0.71	34.08	150	0.95	34.13	27.46
188	1.76	34.34	200	1.90	34.38	27.50
282	2.54	34.59	300	2.65	34.62	27.64
397	3.05	34.74	400	3.10	34.74	27.69
			(600)	3.30	34.81	27.73

Station 4944; July 13; latitude 49°27′ N., longitude 50°32′ W.; depth 329 meters; dynamic height 971.040

0	9.55	32.37	0	9.55	32.37	25.00
23	2.66	32.79	25	2.15	32.84	26.26
46	−1.06	33.18	50	−1.05	33.20	26.72
91	−0.85	33.09	75	−0.95	33.30	26.79
137	−0.76	33.55	100	−0.85	33.37	26.84
183	0.40	33.86	150	−0.50	33.63	27.04
274	0.65	34.30	200	0.50	33.95	27.25
			(300)	0.85	34.42	27.61

Station 4945; July 13; latitude 49°18.5′ N., longitude 51°03′ W.; depth 334 meters; dynamic height 971.034

0	10.40	32.27	0	10.40	32.27	24.78
25	0.67	32.94	25	0.67	32.94	26.43
50	−0.95	33.13	50	−0.95	33.13	26.66
75	−1.04	33.32	75	−1.04	33.32	26.81
100	−1.12	33.46	100	−1.12	33.46	26.93
150	−0.35	33.70	150	−0.35	33.70	27.09
200	0.82	34.02	200	0.82	34.02	27.29
300	2.48	34.54	300	2.48	34.54	27.58

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4946; July 13; latitude 49°09.5′ N., longitude 51°34′ W.; depth 315 meters; dynamic height 971.080

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	10.28	31.84	0	10.28	31.84	24.46
24	------	32.77	25	0.75	32.79	26.31
49	−1.06	33.03	50	−1.05	33.04	26.59
73	−1.17	33.14	75	−1.20	33.15	26.68
97	−1.22	33.22	100	−1.20	33.23	26.74
146	−1.25	33.38	150	−1.25	33.40	26.89
194	−0.72	33.63	200	−0.60	33.67	27.08
291	1.72	-------	(300)	1.95	34.38	27.50

Station 4947; July 13; latitude 49°04′ N., longitude 51°55′ W.; depth 302 meters; dynamic height 971.081

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.52	31.32	0	11.52	31.32	23.84
24	−0.07	32.70	25	−0.15	32.75	26.32
48	−0.75	32.99	50	−0.80	33.00	26.55
71	−1.40	33.12	75	−1.40	33.13	26.67
95	−1.41	33.21	100	−1.40	33.23	26.75
143	−1.22	33.41	150	−1.15	33.45	26.93
191	−0.50	33.71	200	−0.30	33.77	27.15
286	2.10	34.37	(300)	2.50	34.47	27.53

Station 4948; July 13; latitude 49°00.5′ N., longitude 52°08′ W.; depth 293 meters; dynamic height 971.082

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	12.03	30.52	0	12.03	30.52	23.13
20	−1.24	32.77	25	−1.40	32.85	26.44
41	−1.56	32.99	50	−1.60	33.05	26.61
61	−1.62	33.12	75	−1.60	33.17	26.71
82	−1.54	33.20	100	−1.30	33.32	26.82
123	−1.08	33.47	150	−0 90	33.53	26.98
164	−0.84	33.57	200	−0.20	33.74	27.12
221	0.31	33.88				

Station 4949; July 13; latitude 48°54.5′ N., longitude 52°26′ W.; depth 352 meters; dynamic height 971.115

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
-------	11.32	30.71	0	11.32	30.71	23.41
22	−0.21	32.62	25	−0.30	32.68	26.27
45	−0.63	32.88	50	−0.70	32.92	26.48
67	−1.07	33.05	75	−1.15	33.09	26.63
89	−1.28	33.14	100	−1.35	33.18	26.71
134	−1.48	33.27	150	−1.45	33.31	26.81
178	−1.28	33.40	200	−1.00	33.52	26.98
267	0.74	34.00	(300)	1.85	34.24	27.39

Station 4950; July 13–14; latitude 48°48′ N., longitude 52°43′ W.; depth 235 meters; dynamic height 971.138

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.25	30.13	0	11.25	30.13	22.98
24	−0.48	32.75	25	−0.60	32.77	26.35
48	−1.36	32.98	50	−1.40	32.99	26.56
71	−1.59	33.06	75	−1.60	33.07	26.63
95	−1.63	33.13	100	−1.65	33.14	26.68
143	−1.56	33.19	150	−1.55	33.20	26.73
190	−1.27	33.28	(200)	−1.20	33.30	26.80

Station 4951; July 14; latitude 48°46.5′ N., longitude 52°49′ W.; depth 165 meters; dynamic height 971.148

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.60	29.82	0	11.60	29.82	22.67
24	−0.34	32.65	25	−0.40	32.62	26.23
48	−1.21	32.96	50	−1.25	32.97	26.54
72	−1.47	33.04	75	−1.50	33.05	26.60
96	−1.62	33.11	100	−1.65	33.11	26.66
139	−1.59	33.14	(150)	−1.60	33.15	26.69

Station 4952; July 14; latitude 48°44′ N., longitude 52°58′ W.; depth 96 meters; dynamic height 971.164

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	13.06	29.96	0	13.06	29.96	22.51
25	0.76	32.48	25	0.76	32.48	26.06
51	−1.24	32.77	50	−1.20	32.76	26.37
76	−1.39	32.90	75	−1.40	32.90	26.48

Station 4953; July 14; latitude 48°38.5′ N., longitude 52°45′ W.; depth 169 meters; dynamic height 971.155

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	12.56	30.29	0	12.56	30.29	22.86
24	0.82	32.48	25	0.50	32.50	26.08
47	−1.18	32.82	50	−1.20	32.84	26.43
71	−1.36	32.96	75	−1.40	32.98	26.55
94	−1.47	33.04	100	−1.50	33.05	26.60
141	−1.61	33.10	(150)	−1.65	33.11	26.66

Station 4954; July 14; latitude 48°33.5′ N., longitude 52°35′ W.; depth 269 meters; dynamic height 971.137

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.01	30.10	0	11.01	30.10	22.99
25	−0.88	32.72	25	−0.88	32.72	26.32
49	−1.29	32.95	50	−1.30	32.96	26.53
74	−1.55	33.04	75	−1.55	33.04	26.60
98	−1.60	33.11	100	−1.60	33.11	26.66
147	−1.52	33.18	150	−1.50	33.18	26.71
196	−1.50	33.25	200	−1.45	33.26	26.77
245	−0.36	33.47				

Station 4955; July 14; latitude 48°20.5′ N., longitude 52°09′ W.; depth 183 meters; dynamic height 971.116

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	10.85	31.22	0	10.85	31.22	23.88
25	0.00	32.64	25	0.00	32.64	26.23
49	−1.01	32.98	50	−1.05	32.99	26.55
			(75)	−1.35	33.10	26.64
			(100)	−1.40	33.17	26.70
			(150)	−1.20	33.31	26.81

Station 4956; July 14; latitude 48°13.5′ N., longitude 51°55′ W.; depth 187 meters; dynamic height 971.105

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.47	31.56	0	11.47	31.56	24.04
25	−0.19	32.72	25	−0.19	32.72	26.30
50	−1.19	33.03	50	−1.19	33.03	26.58
75	−1.51	33.14	75	−1.51	33.14	26.68
101	−1.54	33.22	100	−1.55	33.22	26.75
151	−1.17	33.41	150	−1.15	33.40	26.89

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STATIONS OCCUPIED IN 1952—Continued

Station 4957; July 14; latitude 48°06′ N., longitude 51°40′ W.; depth 210 meters; dynamic height 971.103

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.30	31.94	0	11.30	31.94	24.36
25	2.05	32.56	25	2.05	32.56	26.04
49	−0.92	33.01	50	−0.95	33.02	26.57
74	−1.23	33.16	75	−1.25	33.16	26.69
99	−1.39	33.28	100	−1.40	33.29	26.79
148	−0.66	33.50	150	−0.65	33.50	26.95
183	−0.25	33.59	(200)	−0.10	33.60	27.00

Station 4958; July 14; latitude 47°58′ N., longitude 51°21′ W.; depth 160 meters; dynamic height 971.098

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.48	31.98	0	11.48	31.98	24.36
25	2.00	32.63	25	2.00	32.63	26.10
49	−0.92	33.04	50	−0.95	33.05	26.59
74	−1.21	33.16	75	−1.25	33.17	26.70
99	−1.28	33.29	100	−1.30	33.30	26.80
148	−0.07	33.61	150	0.00	33.63	27.02

Station 4959; July 14; latitude 47°50.5′ N., longitude 51°03′ W.; depth 115 meters; dynamic height 971.097

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.20	32.05	0	11.20	32.05	24.47
25	0.96	32.58	25	0.96	32.58	26.13
49	−1.03	32.98	50	−1.05	32.99	26.55
74	−0.96	33.18	75	−0.95	33.19	26.71
			(100)	0.10	33.35	26.80

Station 4960; July 14; latitude 47°41.5′ N., longitude 50°41′ W.; depth 134 meters; dynamic height 971.133

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.65	32.03	0	11.65	32.03	24.38
25	8.26	32.08	25	8.26	32.08	24.96
51	−0.39	32.76	50	0.00	32.75	26.32
76	−0.85	33.13	75	−0.85	33.13	26.65
102	−0.54	33.38	100	−0.55	33.36	26.82

Station 4961; July 14; latitude 47°35′ N., longitude 50°25′ W.; depth 201 meters; dynamic height 971.117

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	12.16	32.04	0	12.16	32.04	24.28
25	2.97	32.40	25	2.97	32.40	25.84
51	−0.45	32.81	50	−0.40	32.80	26.38
76	−0.87	32.98	75	−0.85	32.97	26.52
101	−0.53	33.33	100	−0.55	33.32	26.79
152	−0.62	33.44	150	−0.60	33.44	26.89

Station 4962; July 14; latitude 47°23′ N., longitude 49°58′ W.; depth 88 meters; dynamic height 971.135

Observed values			Scaled values			
Depth, meters	Temperature °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.91	32.34	0	11.91	32.34	24.56
26	8.17	32.46	25	8.30	32.46	25.25
52	1.17	32.75	50	1.80	32.73	26.19
78	−0.32	33.00	75	−0.20	32.98	26.51

Station 4963; July 15; latitude 47°47′ N., longitude 49°48′ W.; depth 115 meters; dynamic height 971.113

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	12.01		(0)	12.01	(32.15)	24.40
26	5.95		(25)	6.20	(32.83)	25.84
52	−0.35		(50)	0.25	(32.88)	26.38
78	−0.73		(75)	−0.70	(33.10)	26.62
104	−0.62		(100)	−0.65	(33.19)	26.70

Station 4964; July 15; latitude 47°59.5′ N., longitude 49°43′ W.; depth 170 meters; dynamic height 971.085

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.61	31.87	0	11.61	31.87	24.26
25	−0.29	32.91	25	−0.29	32.91	26.45
51	−0.98	33.05	50	−1.00	33.05	26.59
76	−1.19	33.22	75	−1.20	33.22	26.74
102	−1.44	33.28	100	−1.40	33.28	26.79
153	−0.27	33.69	150	−0.35	33.66	27.06

Station 4965; July 15; latitude 48°10.5′ N., longitude 49°39′ W.; depth 218 meters; dynamic height 971.095

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.19	31.77	0	11.19	31.77	24.26
25	−0.10	32.77	25	−0.10	32.77	26.33
50	−1.27	33.06	50	−1.27	33.06	26.61
76	−1.50	33.18	75	−1.50	33.18	26.71
101	−1.54	33.26	100	−1.55	33.26	26.78
152	−0.99	33.47	150	−1.00	33.46	26.93
202	−0.32	33.69	200	−0.35	33.68	27.07

Station 4966; July 15; latitude 48°31.5′ N., longitude 49°29′ W.; depth 714 meters; dynamic height 970.996

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	11.55	32.11	0	11.55	32.11	24.45
25	1.00	32.95	25	1.00	32.95	26.42
50	1.10	33.33	50	1.10	33.33	26.71
75	−0.76	33.59	75	−0.76	33.59	27.02
100	−0.18	33.79	100	−0.18	33.79	27.16
150	1.42	34.17	150	1.42	34.17	27.38
201	1.92	34.36	200	1.90	34.36	27.49
301	2.62	34.61	300	2.60	34.61	27.63
396	2.79	34.67	400	2.80	34.67	27.66
594	3.32	34.83	600	3.35	34.83	27.73

Station 4967; July 15; latitude 48°39′ N., longitude 49°25′ W.; depth 1,262 meters; dynamic height 970.933

Observed values			Scaled values			
Depth, meters	Temperature, °C	Salinity, ‰	Depth, meters	Temperature, °C	Salinity, ‰	σ_t
0	10.04	32.31	0	10.04	32.31	24.87
25	1.17	33.20	25	1.17	33.20	26.62
50	−0.56	33.64	50	−0.56	33.64	27.05
75	−0.08	33.86	75	−0.08	33.86	27.20
100	0.97	34.09	100	0.97	34.09	27.33
150	2.02	34.41	150	2.02	34.41	27.52
201	2.56	34.58	200	2.55	34.58	27.61
301	3.15	34.77	300	3.15	34.77	27.71
363	*3.55	34.81	400	3.55	34.83	27.71
554	3.43	34.86	600	3.45	34.87	27.76
752	3.49	34.87	800	3.45	34.87	27.76
956	3.26	34.86	1,000	3.25	34.86	27.77
1,113	3.28	34.87				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
Station 4968; July 15; latitude 49°04.5′ N., longitude 49°16′ W.; depth 1,628; meters; dynamic height 970.847						
0	9.17	31.83	0	9.17	31.83	24.64
25	2.88	34.43	25	2.88	34.43	27.46
50	2.62	34.56	50	2.62	34.56	27.59
75	2.71	34.63	75	2.71	34.63	27.63
101	2.87	34.69	100	2.85	34.69	27.67
151	3.23	34.78	150	3.25	34.78	27.70
201	3.31	34.82	200	3.30	34.82	27.74
302	3.31	34.84	300	3.30	34.84	27.75
391	3.27	34.86	400	3.30	34.86	27.77
587	3.28	34.86	600	3.30	34.86	27.77
782	3.29	-------	800	3.30	34.86	27.77
980	3.23	34.86	1,000	3.25	34.86	27.77
1,478	3.31	34.89				
Station 4969; July 15; latitude 49°30.5′ N., longitude 49°10′ W.; depth 1,628 meters; dynamic height 970.835						
0	8.71	32.31	0	8.71	32.31	25.08
25	3.03	34.48	25	3.03	34.48	27.48
51	2.80	34.63	50	2.80	34.63	27.62
76	2.91	34.69	75	2.90	34.68	27.66
102	3.04	34.75	100	3.05	34.74	27.69
152	3.10	34.79	150	3.10	34.79	27.73
203	3.19	34.83	200	3.20	34.83	27.75
305	3.26	34.84	300	3.25	34.845	27.76
401	3.26	34.86	400	3.25	34.86	27.77
600	3.26	34.86	600	3.25	34.86	27.77
800	3.23	34.86	800	3.25	34.86	27.77
1,497	3.32	34.87	1,000	3.20	34.86	27.78
Station 4970; July 15; latitude 50°00′ N., longitude 49°00′ W.; depth 1,847 meters; dynamic height 970.838						
0	10.59	32.77	0	10.59	32.77	25.13
25	3.45	34.51	25	3.45	34.51	27.47
50	2.97	34.65	50	2.97	34.65	27.63
76	3.08	34.71	75	3.10	34.71	27.67
101	3.15	34.77	100	3.15	34.77	27.70
151	3.25	34.80	150	3.25	34.80	27.72
202	3.23	34.81	200	3.25	34.81	27.73
303	3.28	34.85	300	3.30	34.85	27.76
403	3.29	34.85	400	3.30	34.85	27.76
604	3.30	34.86	600	3.30	34.86	27.77
803	3.26	34.86	800	3.30	34.86	27.77
1,004	3.24	34.85	1,000	3.25	34.86	27.77
1,508	3.33	34.89				
Station 4971; July 17; latitude 53°43′ N., longitude 55°48′ W.; depth 110 meters; dynamic height 1454.920						
0	7.49	27.90	0	7.49	27.90	21.80
25	−0.23	32.02	25	−0.23	32.02	25.74
49	−1.61	32.72	50	−1.60	32.72	26.35
74	−1.68	32.78	75	−1.70	32.78	26.39
98	−1.67	32.82	100	−1.65	32.82	26.43
Station 4972; July 17; latitude 53°52′ N., longitude 55°32′ W.; depth 215 meters; dynamic height 1454.841						
0	7.18	31.22	0	7.18	31.22	24.44
23	−0.54	32.56	25	−0.75	32.59	26.22
47	−1.51	32.84	50	−1.55	32.86	26.46
70	−1.49	32.96	75	−1.45	32.97	26.54
93	−1.37	33.02	100	−1.35	33.05	26.60
140	−1.25	33.37	150	−1.00	33.52	26.98
177	0.04	33.92	(200)	1.05	34.26	27.47
Station 4973; July 17; latitude 53°55.5′ N., longitude 55°26′ W.; depth 170 meters; dynamic height 1454.807						
0	7.31	31.57	0	7.31	31.57	24.70
25	−0.28	32.66	25	−0.28	32.66	26.25
49	−1.37	32.97	50	−1.40	32.98	26.55
74	−1.30	33.20	75	−1.30	33.21	26.73
98	−1.22	33.40	100	−1.20	33.41	26.90
147	−0.60	33.78	150	−0.55	33.81	27.19
Station 4974; July 17; latitude 54°05.5′ N., longitude 55°07′ W.; depth 165 meters; dynamic height 1454.795						
0	7.47	31.44	0	7.47	31.44	24.58
25	−0.55	32.77	25	−0.55	32.77	26.35
51	−1.29	33.26	50	−1.30	33.25	26.76
76	−1.26	33.42	75	−1.25	33.42	26.91
101	−1.18	33.58	100	−1.20	33.57	27.03
147	−0.75	33.72	150	−0.70	33.73	27.13
Station 4975; July 17; latitude 54°11′ N., longitude 54°55′ W.; depth 170 meters; dynamic height 1454.790						
0	7.80	31.52	0	7.80	31.52	24.60
25	−1.21	32.87	25	−1.21	32.87	26.46
50	−1.38	33.11	50	−1.38	33.11	26.65
75	−1.22	33.35	75	−1.22	33.35	26.84
101	−1.00	33.60	100	−1.00	33.59	27.03
151	0.09	34.00	150	0.10	33.99	27.20
Station 4976; July 17; latitude 54°30.5′ N., longitude 54°22′ W.; depth 224 meters; dynamic height 1454.812						
0	6.90	31.38	0	6.90	31.38	24.61
25	−1.46	32.89	25	−1.46	32.89	26.47
50	−1.35	33.11	50	−1.35	33.11	26.65
76	−1.29	33.26	75	−1.30	33.25	26.76
101	−1.27	33.40	100	−1.25	33.39	26.88
151	−1.00	33.67	150	−1.00	33.66	27.09
202	−0.21	33.95	200	−0.20	33.94	27.28

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4977; July 17; latitude 54°45′ N., longitude 53°51′ W.; depth 320 meters; dynamic height 1454.720

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σt
0	4.72	32.48	0	4.72	32.48	25.73
23	2.36	33.38	25	2.35	33.47	26.75
45	2.50	33.90	50	2.45	33.94	27.10
68	1.91	34.06	75	1.45	34.07	27.29
90	0.73	34.08	100	0.85	34.14	27.38
135	1.49	34.31	150	1.60	34.33	27.48
180	1.74	34.36	200	1.85	34.38	27.50
270	2.14	34.46	(300)	2.25	34.49	27.56

Station 4978; July 17; latitude 54°51′ N., longitude 53°34′ W.; depth 619 meters; dynamic height 1454.643

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σt
0	7.01	33.26	0	7.01	33.26	26.07
18	2.27	34.01	25	1.35	34.07	27.30
37	0.59	34.14	50	0.90	34.19	27.42
55	1.02	34.22	75	1.65	34.37	27.52
74	1.62	34.36	100	2.25	34.49	27.56
111	2.46	34.53	150	2.85	34.63	27.62
147	2.84	34.62	200	3.10	34.74	27.69
221	3.12	34.78	300	3.15	34.80	27.73
342	3.17	34.80	400	3.20	34.81	27.74
533	3.36	34.85	(600)	3.40	34.86	27.76

Station 4979; July 17; latitude 54°55′ N., longitude 53°23′ W.; depth 1,463 meters; dynamic height 1454.629

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σt
0	7.31	33.69	0	7.31	33.69	26.37
25	4.64	34.31	25	4.64	34.31	27.19
51	3.30	34.46	50	3.30	34.46	27.45
76	2.91	34.61	75	2.90	34.61	27.61
102	2.95	34.68	100	2.95	34.68	27.65
152	3.11	34.77	150	3.10	34.77	27.72
203	3.16	34.78	200	3.15	34.78	27.71
305	3.27	34.83	300	3.30	34.83	27.74
352	3.29	34.84	400	3.30	34.84	27.75
532	3.36	34.855	600	3.40	34.86	27.76
713	3.43	34.87	800	3.45	34.865	27.75
897	3.42	34.865	1,000	3.40	34.86	27.76
1,370	3.35	34.865				

Station 4980; July 17; latitude 55°00′ N., longitude 53°11′ W.; depth 2,067 meters; dynamic height 1454.612

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σt
0	8.10	33.89	0	8.10	33.89	26.40
23	5.98	34.28	25	5.75	34.33	27.07
46	3.46	34.60	50	3.30	34.62	27.58
69	2.97	34.70	75	3.00	34.73	27.69
92	3.20	34.80	100	3.25	34.81	27.73
138	3.35	34.83	150	3.35	34.83	27.73
184	3.40	34.845	200	3.40	34.84	27.74
276	3.28	34.84	300	3.30	34.84	27.75
370	3.37	34.85	400	3.35	34.855	27.75
557	3.41	34.86	600	3.40	34.86	27.76
746	3.46	34.86	800	3.45	34.865	27.75
935	3.36	34.87	1,000	3.35	34.87	27.77
1,419	3.30	34.88	1,500	3.30	34.88	27.78
1,916	3.21	34.90	(2,000)	3.20	34.90	27.81

Station 4981; July 17–18; latitude 55°10.5′ N., longitude 52°51′ W.; depth 2,871 meters; dynamic height 1454.582

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σt
0	8.61	34.33	0	8.61	34.33	26.67
25	7.72	34.41	25	7.72	34.41	26.88
50	3.48	34.64	50	3.48	34.64	27.57
74	3.10	34.75	75	3.10	34.75	27.70
99	3.09	34.755	100	3.10	34.76	27.71
149	3.29	34.85	150	3.30	34.85	27.76
198	3.34	34.87	200	3.35	34.87	27.77
297	3.38	34.88	300	3.40	34.88	27.77
379	3.34	34.88	400	3.35	34.88	27.77
571	3.39	34.89	600	3.35	34.89	27.78
762	3.45	34.91	800	3.45	34.91	27.79
956	3.34	34.90	1,000	3.35	34.90	27.79
1,446	3.22	34.88	1,500	3.20	34.885	27.80
1,945	3.11	34.95	2,000	3.10	34.95	27.86
2,504	2.42	34.92	2,500	2.45	34.92	27.89
2,792	2.08	34.91				

Station 4982; July 18; latitude 55°30′ N., longitude 52°19′ W.; depth 3,200 meters; dynamic height 1,454.577

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σt
0	8.87	34.34	0	8.87	34.34	26.64
25	5.16	34.50	25	5.16	34.50	27.28
49	3.08	34.68	50	3.10	34.68	27.64
74	3.05	34.75	75	3.05	34.75	27.70
98	3.03	34.77	100	3.05	34.77	27.72
147	3.19	34.83	150	3.20	34.83	27.75
197	3.26	34.85	200	3.25	34.85	27.76
295	3.30	34.865	300	3.30	34.865	27.77
394	3.28	34.87	400	3.30	34.87	27.78
592	3.33	34.89	600	3.30	34.885	27.79
790	3.26	34.88	800	3.25	34.88	27.78
989	3.25	34.88	1,000	3.25	34.88	27.78
1,475	3.21	34.88	1,500	3.25	34.88	27.78
1,954	3.27	34.885	2,000	3.30	34.89	27.79
2,416	2.98	34.94	2,500	2.85	34.94	27.87
2,893	......	34.92	3,000	1.90	34.90	27.92
3,038	1.78	34.89				

Station 4983; July 18; latitude 55°55.5′ N., longitude 51°34′ W.; depth 3,402 meters; dynamic height 1,454.650

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σt
0	9.62	34.42	0	9.62	34.42	26.59
25	8.79	34.47	25	8.79	34.47	26.76
49	5.65	34.59	50	5.60	34.59	27.30
74	4.83	34.62	75	4.80	34.62	27.42
99	4.38	34.64	100	4.35	34.64	27.48
148	3.91	34.71	150	3.90	34.71	27.59
197	3.68	34.73	200	3.65	34.73	27.62
296	3.48	34.83	300	3.50	34.83	27.72
398	3.57	34.89	400	3.55	34.89	27.76
596	3.50	34.88	600	3.50	34.88	27.76
792	3.40	34.88	800	3.40	34.88	27.77
988	3.36	34.88	1,000	3.35	34.88	27.77
1,486	3.32	34.90	1,500	3.35	34.90	27.79
1,987	3.37	34.95	2,000	3.40	34.95	27.83
2,335	3.12	34.91	2,500	3.05	34.93	27.84
2,801	2.79	34.94	3,000	2.50	34.91	27.88
3,126	2.31	34.91				

Table of Oceanographic Data—Continued

STATIONS OCCUPIED IN 1952—Continued

Station 4984; July 18; latitude 56°30.5′ N., longitude 50°25′ W.; depth 3,530 meters; dynamic height 1,454.602

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	8.25	34.47	0	8.25	34.47	26.84
26	6.66	34.54	25	6.75	34.54	27.11
51	3.97	34.69	50	4.00	34.69	27.56
77	3.29	34.79	75	3.30	34.79	27.71
103	3.25	34.79	100	3.25	34.79	27.71
153	3.15	34.84	150	3.15	34.84	27.76
204	3.09	34.84	200	3.10	34.83	27.76
307	3.28	34.87	300	3.25	34.855	27.76
310	3.24	34.86	400	3.20	34.84	27.76
495	3.11	34.85	600	3.15	34.84	27.76
700	3.14	34.84	800	3.15	34.84	27.76
924	3.13	34.84	1,000	3.15	34.84	27.76
1,427	3.16	34.835	1,500	3.15	34.84	27.76
1,956	3.20	34.86	2,000	3.25	34.86	27.77
2,532	3.40	34.915	2,500	3.40	34.91	27.80
3,016	3.00	34.94	3,000	3.00	34.94	27.86
3,405	2.51	34.92	(3,500)	2.40	34.92	27.90

Station 4985; July 19; latitude 57°02′ N., longitude 49°02′ W.; depth 3,475 meters; dynamic height 1,454.617

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	8.89	34.39	0	8.89	34.39	26.67
24	6.95	34.47	25	6.85	34.47	27.05
49	4.29	34.60	50	4.20	34.60	27.47
74	3.20	34.70	75	3.20	34.70	27.65
99	3.30	34.74	100	3.30	34.74	27.67
148	3.28	34.79	150	3.30	34.79	27.71
197	3.34	34.81	200	3.35	34.81	27.72
296	3.21	34.83	300	3.20	34.83	27.75
379	3.23	34.84	400	3.25	34.84	27.75
568	3.27	34.84	600	3.25	34.84	27.75
758	3.27	34.83	800	3.25	34.845	27.76
948	3.26	34.85	1,000	3.25	34.85	27.76
1,442	3.21	34.86	1,500	3.20	34.86	27.78
1,948	3.44	34.90	2,000	3.45	34.90	27.78
2,552	3.09	34.91	2,500	3.15	34.91	27.82
3,040	2.65	34.91	3,000	2.70	34.91	27.86
3,429	1.87	34.88				

Station 4986; July 19; latitude 57°34.5′ N., longitude 48°04′ W.; depth 3,347 meters; dynamic height 1454.603

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	7.72	34.43	0	7.72	34.43	26.89
25	5.23	34.47	25	5.23	34.47	27.25
52	3.04	34.69	50	3.05	34.67	27.64
77	3.19	34.79	75	3.15	34.79	27.72
104	3.33	34.795	100	3.30	34.80	27.72
154	3.41	34.85	150	3.40	34.85	27.75
206	3.45	34.87	200	3.45	34.86	27.75
310	3.36	34.85	300	3.35	34.85	27.75
513	3.42	34.86	400	3.40	34.855	27.75
719	3.29	34.84	600	3.35	34.85	27.75
924	3.24	34.85	800	3.25	34.84	27.75
1,129	3.22	34.86	1,000	3.25	34.85	27.76
1,646	3.27	34.85	1,500	3.25	34.86	27.77
2,164	3.23	34.89	2,000	3.25	34.88	27.78
2,453	3.00	34.89	2,500	2.95	34.89	27.82
2,937	2.46	34.91	3,000	2.35	34.91	27.89
3,227	1.87	34.89				

Station 4987; July 19; latitude 58°05.5′ N., longitude 47°01′ W.; depth 3,054 meters; dynamic height 1454.603

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	7.66	34.49	0	7.66	34.49	26.94
25	6.43	34.52	25	6.43	34.52	27.14
50	5.44	34.63	50	5.44	34.63	27.34
75	3.40	34.76	75	3.40	34.76	27.68
100	3.60	34.82	100	3.60	34.82	27.71
150	3.58	34.845	150	3.58	34.845	27.73
199	3.59	34.845	200	3.60	34.845	27.73
299	3.84	34.90	300	3.85	34.90	27.74
406	3.37	34.85	400	3.40	34.85	27.75
609	3.46	34.87	600	3.45	34.87	27.76
812	3.44	34.89	800	3.45	34.89	27.77
1,015	3.43	34.895	1,000	3.45	34.895	27.78
1,494	3.37	34.915	1,500	3.40	34.91	27.80
2,044	3.23	34.915	2,000	3.25	34.91	27.81
2,490	2.77	34.92	2,500	2.75	34.92	27.87
2,986	1.67	34.87	(3,000)	1.60	34.87	27.92

Station 4988; July 20; latitude 58°37.5′ N., longitude 45°57′ W.; depth 2,505 meters; dynamic height 1454.604

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.80	34.49	0	6.80	34.49	27.06
25	5.22	34.55	25	5.22	34.55	27.32
51	4.43	34.67	50	4.45	34.67	27.50
76	3.77	34.85	75	3.75	34.85	27.71
101	3.76	34.86	100	3.75	34.86	27.72
152	4.10	34.92	150	4.10	34.92	27.74
203	3.92	34.905	200	3.95	34.91	27.74
304	3.71	34.885	300	3.70	34.89	27.75
376	3.59	34.895	400	3.55	34.885	27.76
565	3.49	34.885	600	3.50	34.875	27.76
755	3.45	34.85	800	3.45	34.87	27.76
946	3.42	34.84	1,000	3.45	34.87	27.76
1,431	3.39	34.87	1,500	3.35	34.87	27.77
1,926	3.00	34.895	2,000	2.90	34.895	27.84
2,448	2.08	34.84	(2,500)	1.95	34.83	27.86

Station 4989; July 20; latitude 59°00′ N., longitude 45°16′ W.; depth 2,286 meters; dynamic height 1454.582

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, ‰	Depth, meters	Temperature, ° C	Salinity, ‰	σ_t
0	6.99	34.64	0	6.99	34.64	27.15
25	5.60	34.64	25	5.60	34.64	27.34
49	4.98	34.79	50	4.95	34.79	27.53
74	4.62	34.885	75	4.60	34.89	27.65
98	4.35	34.93	100	4.35	34.93	27.71
147	4.20	34.95	150	4.20	34.95	27.75
196	4.08	34.94	200	4.05	34.94	27.75
294	3.72	34.88	300	3.70	34.885	27.75
393	3.83	34.92	400	3.80	34.92	27.77
591	3.66	34.915	600	3.65	34.91	27.77
789	3.53	34.90	800	3.55	34.90	27.77
988	3.47	34.90	1,000	3.50	34.90	27.78
1,492	3.29	34.91	1,500	3.30	34.91	27.81
2,002	2.80	34.92	2,000	2.80	34.92	27.86
2,253	2.14	34.875				

STATIONS OCCUPIED IN 1952—Continued

Station 4990; July 20; latitude 59°14.5′ N., longitude 44°54′ W.; depth 1,957 meters; dynamic height 1454.616

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	5.68	34.34	0	5.68	34.34	27.09
25	5.61	34.41	25	5.61	34.41	27.16
50	5.54	34.89	50	5.54	34.89	27.54
76	5.43	34.99	75	5.40	34.99	27.64
101	5.32	35.01	100	5.35	35.01	27.66
151	5.01	34.995	150	5.05	34.995	27.69
202	4.80	34.99	200	4.80	34.99	27.71
303	4.43	34.99	300	4.45	34.99	27.75
404	4.24	34.95	400	4.25	34.96	27.75
605	3.89	34.93	600	3.90	34.93	27.76
806	3.49	34.88	800	3.50	34.88	27.76
1,005	3.46	34.89	1,000	3.50	34.89	27.77
1,506	3.32	34.87	1,500	3.35	34.87	27.77
1,862	2.81	34.89				

Station 4991; July 20; latitude 59°21.5′ N., longitude 44°41′ W.; depth 1,097 meters; dynamic height 1454.676

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	5.27	34.05	0	5.27	34.05	26.91
24	5.46	34.46	25	5.50	34.47	27.22
49	5.71	34.71	50	5.70	34.71	27.38
74	5.87	34.87	75	5.85	34.87	27.49
99	5.48	34.92	100	5.45	34.92	27.58
148	4.78	34.96	150	4.75	34.96	27.69
197	4.52	34.92	200	4.50	34.92	27.69
429	4.69	34.97	300	4.60	34.94	27.69
635	4.66	34.97	400	4.70	34.97	27.71
838	4.18	34.93	600	4.65	34.97	27.72
1,036	4.01	34.93	800	4.25	34.935	27.73
			1,000	4.05	34.93	27.74

Station 4992; July 20; latitude 59°31.5′ N., longitude 44°31′ W.; depth 179 meters; dynamic height 1454.811

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	−0.18	30.99	0	−0.18	30.99	24.90
23	−0.36	31.27	25	−0.40	31.38	25.23
47	−0.93	32.55	50	−0.90	32.66	26.28
70	−0.81	33.37	75	−0.65	33.47	26.93
94	0.11	33.87	100	0.50	33.94	27.24
140	2.91	34.49	150	3.35	34.61	27.56
159	3.66	34.70				

Station 4993; July 20; latitude 59°34.5′ N., longitude 44°23′ W.; depth 153 meters; dynamic height 1454.839

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	−0.20	31.22	0	−0.20	31.22	25.09
25	−0.53	31.61	25	−0.53	31.61	25.42
51	−0.84	32.84	50	−0.80	32.79	26.38
76	−1.01	33.12	75	−1.00	33.10	26.63
101	−0.97	33.56	100	−0.95	33.54	26.99
147	0.46	33.88	150	0.60	33.89	27.19

Station 4994; July 20; latitude 59°36′ N., longitude 44°11′ W.; depth 165 meters; dynamic height 1454.854

Observed values			Scaled values			
Depth, meters	Temperature, ° C	Salinity, °/oo	Depth, meters	Temperature, ° C	Salinity, °/oo	σ_t
0	−0.78	31.12	0	−0.78	31.12	25.03
25	−0.31	31.38	25	−0.31	31.38	25.22
51	−0.69	32.26	50	−0.70	32.23	25.92
76	−0.52	32.90	75	−0.55	32.87	26.43
101	−0.30	33.47	100	−0.30	33.44	26.88
152	1.70	34.25	150	1.60	34.21	27.39

Contribution No. 651

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Observations of Pelagic Fishes of the Tropical Atlantic[1]

FRANK J. MATHER III AND C. GODFREY DAY

THE presence of research vessels of the Woods Hole Oceanographic Institution in the tropical Atlantic during much of the year 1952 afforded the opportunity for an incidental study of the pelagic fishes of the region. A hydrographic survey sponsored by the Office of Naval Research was carried out there in the winter and early spring by the ATLANTIS (cruise 178) and the ALBATROSS III (cruise A42). The authors, one aboard each vessel, devoted much of their spare time to collecting data on the pelagic fishes encountered. Carl Speight of the ATLANTIS' crew took a very keen and helpful interest in this work, and when this vessel returned to the area in August for cruises 180 (a geological study by the Lamont Observatory of Columbia University) and 181 (a hydrographic survey), he volunteered to continue the collection of pelagic fishes as an extra activity. With the assistance of others of the ships' companies and scientific parties, some very fine specimens were taken. These observations have been supplemented by similar ones recorded by Mather during passages of the ATLANTIS (cruise 151) from Bermuda to Gibraltar (Dec., 1947–Jan., 1948) and return (May–June, 1948). Although all of these efforts had to be made to fit the exigencies of other work, nearly 80 observations were recorded.

Fishing was conducted chiefly by trolling, though all catches of sharks were made while the ships were hove to on stations. Trolling speeds averaged 8 knots for ATLANTIS and 12 knots for ALBATROSS III.

The locations of the observations are shown on the orientation chart (Fig. 1). For comparative purposes, we have divided the region into three areas, which are roughly based on hydrographic considerations. Area I is mainly in the Sargasso Sea, area II takes in the colder water near the African coast, while area III is in the equatorial current system.

All observations are arranged according to species (Table I), and numbers are used to designate the respective observatons on the chart and in the text. Sharks were measured from the snout to the tip of the upper caudal lobe; teleostean fishes from snout to fork of tail. Figures in parentheses are estimates. Observations from which specimens or skeletons with head and fins were preserved are marked with an asterisk (*). During cruises 180 and 181, no consistent record of fish lost or sighted was kept.

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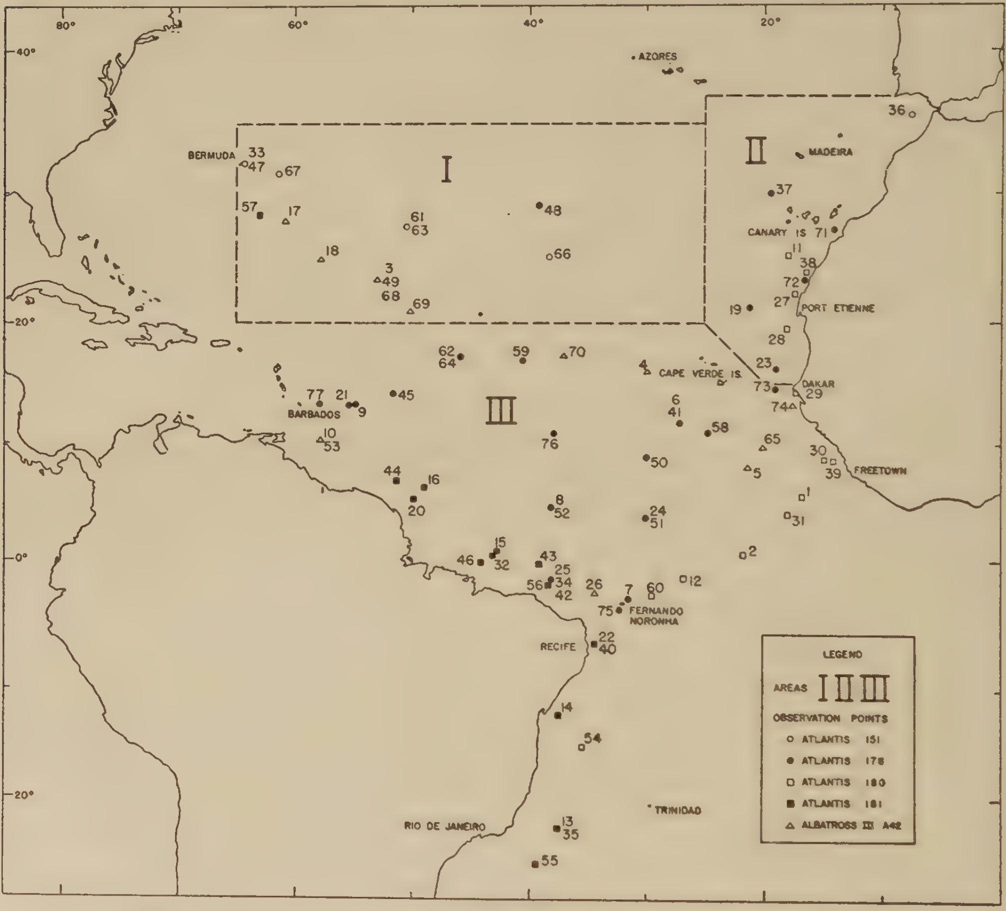
[1] Contribution No. 651 from the Woods Hole Oceanographic Institution.

THE OBSERVATIONS CONSIDERED BY SPECIES

A discussion of some of the species observed, with emphasis on what appear to be unusual or little-known occurrences, is presented below. Wherever temperature preferences appear probable, mention is made of them. The three areas are compared for general productivity of potentially valuable fish.


80°
60°
40°
20°
40°
20°
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20°
AZORES
MADEIRA
BERMUDA
CANARY IS
PORT ETIENNE
CAPE VERDE IS
DAKAR
FREETOWN
BARBADOS
FERNANDO NORONHA
RECIFE
TRINIDAD
RIO DE JANEIRO
I
II
III
LEGEND
AREAS I II III
OBSERVATION POINTS
○ ATLANTIS 151
● ATLANTIS 178
□ ATLANTIS 180
■ ATLANTIS 181
△ ALBATROSS III A42

Fig. 1. Orientation chart of cruises of the ATLANTIS and the ALBATROSS III

Carcharhinus longimanus (Poey): The white-tipped shark was by far the most abundant and widely distributed pelagic shark in the area. Sixteen were caught and about 16 others were seen, while only three sharks of all other species combined were taken. The recorded occurrences of white-tipped sharks were in temperatures ranging from 72.6° to 82.4° F. They were taken in all three areas, but were most common in area III.

Sphyraena barracuda (Walbaum): The capture of a great barracuda over 270 miles from the nearest shoal water (observation 21) was of interest because this species is generally believed to frequent reefs or banks and to wander only relatively short distances out into deep water. Other offshore records of this species obtained from the ATLANTIS include three individuals taken by Harold Backus at the Brownson Deep, about 80 miles north of Mona Passage in March, 1949, and one taken September 11, 1953, at 38°16′ N and 69°10′ W, about 280 miles south of Cape Cod.

Katsuwonus pelamis (Linnaeus): Although the oceanic bonito or skipjack is one of the mainstays of the high seas tuna fishery of the Pacific, we found no indication that it is comparably abundant in the Atlantic. A single rather large specimen (observation 24) was taken in mid-ocean, but the only schools

Table I

List of Observations

Observation Nos.	Species	Caught	Lost	Sighted	Length in cm.	Month	Lat.	Long.	Surf. temp., °F
1	*Prionace glauca*	1			(250)	Sep. '52	5°23′N	17°00′W	80.6
2	(Great blue shark)	1			(300)	Sep. '52	0°35′N	21°35′W	77.0
3	*Carcharhinus longimanus*	1	1			Feb. '52	23°28′N	53°01′W	75.5
4	(White-tipped shark)	1				Feb. '52	15°56′N	30°03′W	72.6
5				1	(150)	Feb. '52	7°50′N	21°26′W	78.7
6		1			166	Mar. '52	11°48′N	27°10′W	74.1
7			1	1	(175)	Mar. '52	3°17′S	31°37′W	82.4
8		2		1–2	156–163	Mar. '52	4°37′N	38°09′W	80.0
9			1		(165)	Apr. '52	13°17′N	54°57′W	80.1
10		2	1	(7)		Apr. '52	10°17′N	57°53′W	80.9
11		1			(240)	Aug. '52	25°18′N	18°04′W	73.4
12		1			(155)	Sep. '52	1°27′S	26°51′W	78.0
13		1				Oct. '52	22°21′S	37°39′W	74.5
14		1				Oct. '52	13°03′S	37°30′W	79.8
15		3				Nov. '52	0°49′N	42°46′W	81.8
16		2				Nov. '52	6°12′N	48°58′W	81.6
17	Unidentified shark			1	(Large)	Feb. '52	27°51′N	60°51′W	62.0
18				1	(Large)	Feb. '52	25°05′N	57°50′W	74.5
19				1		Feb. '52	21°12′N	21°16′W	66.4
20		1			60	Nov. '52	5°20′N	49°53′W	81.4
21	*Sphyraena barracuda*	1			107	Apr. '52	13°19′N	55°25′W	80.4
22*	(Great barracuda)	1			70	Oct. '52	7°00′S	34°30′W	79.6
23	*Katsuwonus pelamis*	2	5		46–48	Feb. '52	16°17′N	19°08′W	67.2
24*	(Oceanic bonito)	1			72	Mar. '52	3°34′N	30°11′W	81.7
25*	*Euthynnus alletteratus* (Little tuna)	2			63–67	Mar. '52	1°35′S	38°10′W	83.1
26	*Neothunnus albacares*			(100)	(220)	Mar. '52	2°44′S	34°33′W	82.6
27*	(Yellowfin tuna) (a)	3			59	Aug. '52	22°13′N	17°27′W	68.3
28	(a)	3				Aug. '52	19°26′N	18°06′W	79.7
29	(a)	1				Aug. '52	14°39′N	17°20′W	
30	(a)	2				Sep. '52	8°47′N	14°57′W	79.8
31*		1	1		143	Sep. '52	4°00′N	18°00′W	80.1
32				(1500)	(100)	Nov. '52	0°32′N	43°15′W	81.0
33	*Parathunnus atlanticus*	1			50	Jun. '48	32°21′N	64°37′W	76.2
34*	(Blackfin tuna)	5	1		61–78	Mar. '52	1°35′S	38°10′W	83.1
35*		1			71	Oct. '52	22°21′S	37°37′W	74.5
36*	*Thunnus thynnus* (Bluefin tuna)	1			52	Jan. '48	35°40′N	7°48′W	63.6

TABLE I (*Continued*)

Observation Nos.	Species	Caught	Lost	Sighted	Length in cm.	Month	Lat.	Long.	Surf. temp., °F
37	*Thunnus* sp. (b) (Unidentified tuna)		1		(40)	Feb. '52	30°05′N	19°34′W	64.5
38*	*Sarda sarda* (Atlantic bonito)	1			41	Aug. '52	24°02′N	16°28′W	67.5
39*	*Scomberomorus maculatus* (Spanish mackerel)	1			54	Sep. '52	8°22′N	14°06′W	79.5
40	*Scomberomorus cavalla* (King mackerel)	1				Oct. '52	7°00′S	34°29′W	79.6
41*	*Acanthocybium solandri* (Wahoo)	1			162	Mar. '52	11°48′N	27°10′W	74.1
42*		1			144	Mar. '52	1°35′S	38°10′W	83.1
43*		1			126	Nov. '52	0°19′S	39°16′W	80.0
44		1			140	Nov. '52	6°52′N	51°19′W	81.2
45*	*Gempylus serpens* (Snake mackerel)	1			100	Apr. '52	14°08′N	51°37′W	79.0
46	*Makaira nigricans ampla* (Blue marlin) (c)	1			250	Nov. '52	0°08′S	44°10′W	80.2
47	*Seriola falcata* (Falcate amberjack)	1			57	Dec. '47	32°21′N	64°37′W	68.9
48	*Coryphaena hippurus* (Common dolphin)	1			79	Feb. '52	29°04′N	39°19′W	70.8
49		2		(50)		Feb. '52	23°28′N	53°01′W	75.5
50				(5)	(60)	Mar. '52	8°42′N	29°57′W	75.0
51			1		(90)	Mar. '52	3°34′N	30°11′W	81.7
52				(100)	(75–100)	Mar. '52	4°37′N	38°09′W	81.0
53				(12)	(75)	Apr. '52	10°17′N	57°53′W	80.9
54		2			86–137	Sep. '52	15°41′S	35°27′W	78.0
55		1				Oct. '52	25°08′S	39°26′W	70.8
56		1			(Large)	Nov. '52	2°01′S	38°29′W	79.8
57		1			61	Dec. '52	28°22′N	63°05′W	74.9
58	*Coryphaena equisetis* (Little dolphin) (d)	1			30	Feb. '52	10°57′N	24°45′W	75.9
59		1			43	Mar. '52	16°58′N	40°38′W	75.9
60*		6			46	Sep. '52	2°54′S	29°39′W	78.2
61	*Coryphaena* sp. (Unidentified dolphin)			1–2	(Small)	Jun. '48	27°26′N	50°23′W	77.0
62				1	(35)	Apr. '52	17°19′N	45°51′W	78.3
63	Unidentified trigger-fish	(10)		(100)	(35)	Jun. '48	27°26′N	50°23′W	77.0
64				(20)	(35)	Apr. '52	17°19′N	45°51′W	78.3

TABLE I (*Continued*)

Observation Nos.	Species	Caught	Lost	Sighted	Length in cm.	Month	Lat.	Long.	Surf. temp., °F
65	*Mola mola* (Ocean sunfish)			1	(200)	Feb. '52	9°40'N	20°03'W	76.6
66	Unidentified fishes		1		?	Jun. '48	25°11'N	38°22'W	74.3
67			1		(Large)	Jun. '48	31°25'N	61°27'W	77.5
68			1		(Large)	Feb. '52	23°28'N	53°01'W	75.5
69			1		(Med.)	Feb. '52	20°56'N	50°17'W	75.7
70			1		(Large)	Feb. '52	17°15'N	37°17'W	74.3
71			1		(75)	Feb. '52	27°11'N	14°09'W	63.9
72			1		(Large)	Feb. '52	23°18'N	16°45'W	66.2
73			1		(Large)	Feb. '52	14°35'N	19°02'W	67.9
74	(e)			Many	(Large)	Feb. '52	13°15'N	17°40'W	65.±
75	(f)		2		(Large)	Mar. '52	4°08'S	32°20'W	82.3
76			2		(Large)	Mar. '52	10°51'N	37°52'W	78.1
77			1		(Large)	Apr. '52	13°07'N	57°56'W	80.5

* Specimens or skeletons with head and fins were preserved.

(a) One specimen from observation 27 was preserved, measured, and identified. The others from observations 27–30 were reported to be of the same species and of about the same size as this specimen.

(b) Probably *Neothunnus albacares* or *Parathunnus obesus*.

(c) Measured from tip of bill to tip of caudal.

(d) One specimen was preserved, measured, and identified. The others were reported to be of the same species and of about the same size.

(e) Acres of bait chased by large fish.

(f) East of Fernando Noronha Island near this position about 7 areas densely covered by actively working sea birds were observed.

encountered were small ones found close to Dakar (observation 23).

Parathunnus atlanticus (Lesson): Observations made by us during and since these cruises, together with records from the literature, enable us to clarify and expand the picture of the distribution of this long neglected but important species. The blackfin tuna has rarely been recorded from waters south of the Caribbean. Beebe and Tee-Van (1936) showed that this was a valid species first figured and described by Lesson (1830) from Trinidad Island off Brazil (20° south latitude) as *Thynnus atlanticus*, and that Cuvier and Valenciennes described the same fish from Lesson's drawing as a new species, *Thynnus balteatus*. Prior to Beebe and Tee-Van's work most authors had placed these names in the synonymy of *Germo alalunga*, the true albacore of the eastern Atlantic and the Pacific.

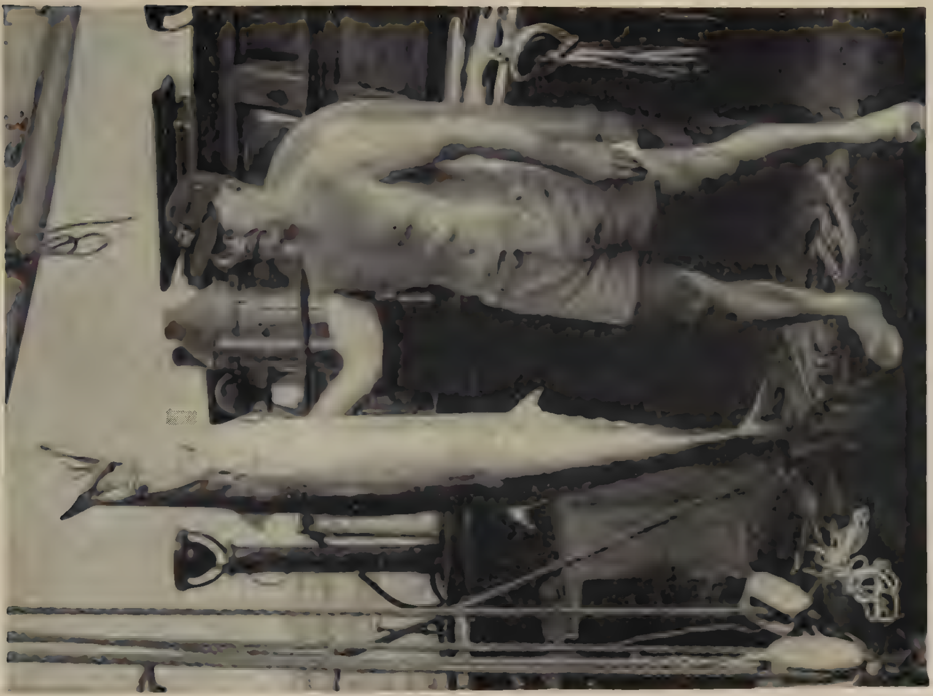
The only other record we have found of the blackfin tuna from the southern Atlantic is based on the listing by Ribeiro (1915) of *Germo alalunga* among the fishes of Brazil, Fowler (1941) used this record as it stood but in 1944 he placed it in the synonymy of *Parathunnus atlanticus*. Ribeiro's description, based on a specimen about 50 cm. long taken at Rio de Janeiro, is quite meager, and while some of the characters given apply to the blackfin tuna, others, such as the length of the pectoral fins in adults, definitely do not. On the basis of the published information, we would find it impossible to identify this specimen positively.

Our observation 35, made on an uncharted shoal off Brazil at 22° south latitude, gives positive confirmation of the occurrence of the blackfin tuna in this region, and substantiates the deductions of Beebe and Tee-Van concerning *Thynnus atlanticus* of Lesson.

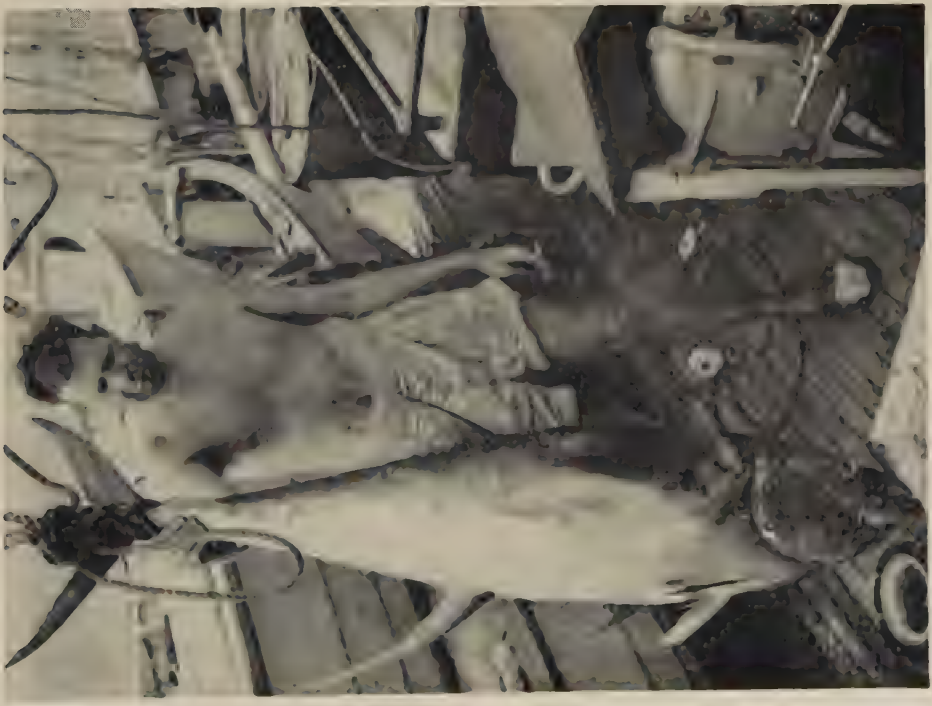
A blackfin tuna was seen by us in the market at Recife, Brazil, and 5 others were taken over a shoal off the north coast of that country (observation 34). Several specimens were seen in the market at Barbados. Thus it seems that the species ranges along the coasts and among the outlying islands and banks from at least as far south as Rio de Janeiro to the Antilles. The species has been recorded throughout the West Indies as follows: from Haiti, by Beebe and Tee-Van (1928), as *Parathunnus obesus*; from the Grenadines, by Beebe and Hollister (1935); from Tobago, St. Lucia, and Grenada, by Beebe and Tee-Van (1936). Mendes and Whiteleather have told us of its presence off the north coast of Venezuela, and Fowler (1944) and Mather and Schuck (1952) have reported it from the western Caribbean. Stuart Springer, of the U. S. Fish & Wildlife Service, and J. L. Baughman (1950) have reported it from the Gulf of Mexico. We have seen specimens at Miami, Florida, where it was described by Fowler (1934) as *Parathunnus rosengarteni*, and in the Bahama Islands. We have also seen it at Bermuda, where it is very abundant and was first described by Mowbray (1935) as *Parathunnus ambiguus*. The northernmost limit of its ordinary range along the coast of the United States must be near Cape Hatteras, where a specimen was reported by Shuck and Mather (1951), and sixteen additional ones were identified by Mather in October, 1952. The northern record for the species is from off Martha's Vineyard, Massachusetts (Mather and Shuck, 1952). It does not appear to range very far outside the 100 fathom curve, though one was taken August 27, 1953, from the ATLANTIS at 35°54′ N, 69°31′ W, about 300 miles east of Cape Hatteras. Observations 34 and 35 were made over uncharted offshore banks. L. S. Mowbray has expressed the opinion that the Bermuda blackfins form a discrete population (Oceanic Fisheries Conference, Bermuda, June, 1951). The range of this species appears to be limited to the western Atlantic, and it occurs in area I only in the vicinity of Bermuda. It would be of interest, however, to compare individuals of this species with small specimens of the similar *Parathunnus obesus* (Lowe) of the eastern Atlantic.

The commercial possibilities of the species appear to be worth consideration. The flesh is of excellent quality, comparable to yellowfin tuna. Mowbray reports a maximum size for the species of 60 lbs., but we have not seen any over 25 lbs. and most of the individuals we have examined weighed less than 10 lbs. Therefore, the capture and processing of this fish would not be as difficult or expensive as is true of the larger tunas, an important consideration in undeveloped areas. The fact that the species schools densely should also be favorable to commercial fishing. A small tuna canning industry in western Cuba is supported by blackfin tuna and skipjack (Rawlings, 1953).

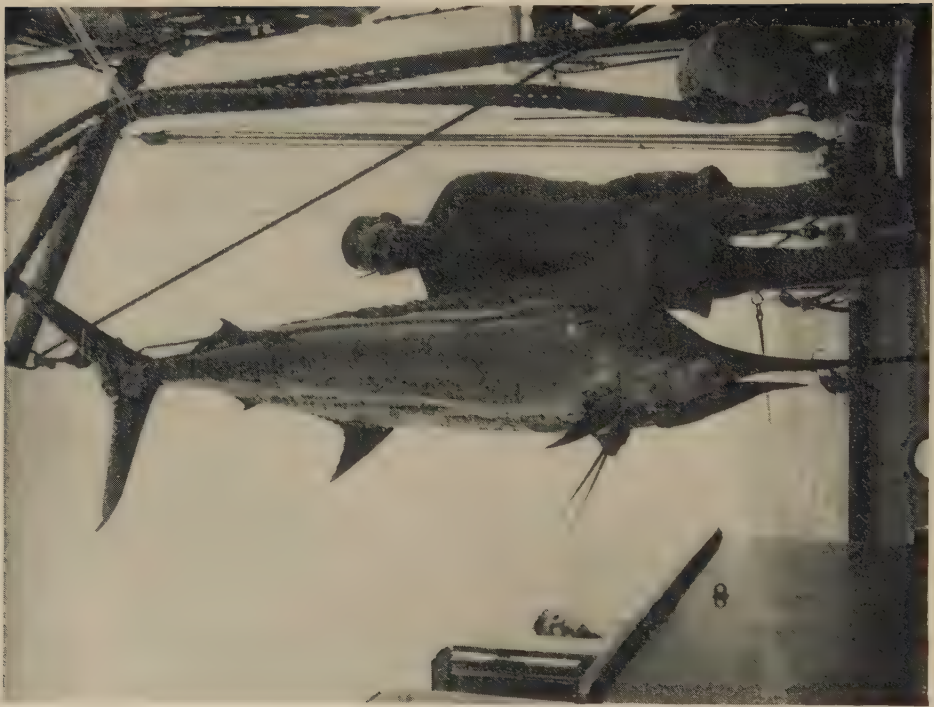
Neothunnus albacares (Bonnaterre): As the yellowfin tuna is perhaps the most important species taken in the high seas fishery of the Pacific, offshore records of it in the Atlantic such as our observations 26, 31 and 32 are of special interest. The specimen taken at 31 (Pl. I) was 143 cm. long, which corresponds to a weight of about 130 lbs. A similar fish parted a line at the same time. Those seen at observation 26 were especially large. They were playing on the surface close to the vessel and an observer who was very familiar with giant bluefin tuna estimated their weight at 400 lbs. That yellowfin tuna actually reach this great size has been confirmed by Mr. Dudley W. Wiles, Fishery Officer, Barbados, B.W.I., and by Mr. G. Blanche, Administrateur Principal de l'Inscription Maritime, Fort-de-France, Martinique, who have actually seen such fish brought in by commercial fishermen at their respective islands. Cunningham (1910) was told that the largest yellowfin tuna taken at St. Helena in the last few years before his visit weighed 400 lbs. Very large numbers of tuna believed to be yellowfins about 1 meter long were seen at observation 32. While these records are too few to justify drawing conclusions they are certainly sufficient to arouse a desire for further investigation. This is especially indicated as the U. S. Fish & Wildlife Service Laboratory at Honolulu has found that this species is abundant at convergences in the equatorial current system of the Pacific. There they are taken by long-line (deep) fishing and are seldom seen or caught on the surface. Our few efforts at deep fishing with single lines when the vessels were hove to were unsuccessful, but this is not surprising in view of the brief duration of these attempts and the limited number of lines used. The knowledge of the equatorial current system which is being gained should be of value in planning any future exploratory fishing. The yellowfin tuna were taken or seen over a



A wahoo, probably the first recorded from the eastern Atlantic (observation 41).



A 143-cm. yellowfin tuna taken 350 miles SW of Freetown, Sierra Leone (observation 31).



A 250-cm. blue marlin taken in the Guiana current off the coast of Brazil (observation 46).

A 100-cm. snake mackerel taken about 500 miles east of Barbados (observation 45).

wide range of surface temperatures from 68.3° to 82.6° F. They appear to be especially abundant near the African coast.

Scomberomorus maculatus (Mitchill): The status of the Spanish mackerel of the eastern Atlantic is in question. Postel (1950), Cadenat (1950), Fraser-Brunner (1950), and Chabanaud and Monod (1926) listed it as a distinct species under the name *Cybium tritor* (Cuvier and Valenciennes, 1831). Fowler (1936) and Scaccini (1941) placed this name in the synonymy of *Scomberomorus maculatus* (Mitchill, 1815), and Smith (1949) and Lozano Cabo (1950) also applied the latter name to the West African fish.

While biometric and anatomical studies requiring many specimens would be necessary to settle this question definitively, we have made a preliminary effort with the material available (Table II). Two eastern Atlantic specimens (one from the Canary Islands at the Harvard Museum of Comparative Zoology and our specimen from observation 39) and seven Spanish mackerel from the western Caribbean and the Gulf of Mexico were measured, following the method of Marr and Schaefer (1949). The average measurements of 142 specimens from Dakar published by Postel (1950) were converted to this system. Counts published by Fowler (1936) from a small specimen taken off Liberia are also included. These data indicate the following differences between the seven specimens from the Caribbean and Gulf and those from the eastern Atlantic: (1) The second dorsal and ventral fins of 144 eastern Atlantic specimens were inserted more posteriorly (.515 and .26 of fork length, respectively) than those of the Caribbean and Gulf specimens (.50 and .25 of fork length, respectively); (2) The pectoral fins of 144 eastern Atlantic fish were longer (.136+ of fork length) than those of the latter fish (.125 of fork length); and (3) Three eastern Atlantic specimens had 16 or 17 first dorsal spines while the 7 Caribbean and Gulf fish had 17 or 18.

These slight differences appear to be racial rather than specific and until more important ones are shown we must consider the West African fish to be the same species as the American one, whose name, *Scomberomorus maculatus*, has priority. If the differences found were consistent in adequate series of specimens from each region, it would show that at least two races of the species exist, one in the eastern Atlantic and one off the east coast of the Americas, and that there is little interchange between these populations.

TABLE II

MEASUREMENTS AND COUNTS OF *Scomberomorus maculatus*

Average measurements in percentage of fork length

Measurement	Locality and number of specimens			
	Gulf and Caribbean (7)	Sierra Leone (1)	Canary Islands (1)	Dakar (142)
Head length	.214	.222	.211	.205
Snout to 1st dorsal insertion	.250	.259	.255	.245
Snout to 2nd dorsal insertion	.502	.515	.513	.515
Snout to ventral insertion	.250	.276	.260	.260
Snout to anal insertion	.533	.530	.513	.532
Maximum depth	.180*	.175	.177	...
Depth at 1st dorsal insertion	.150*	.161	...	.156†
Length of pectoral	.125	.138	.144	.136
Length of maxillary	.120	.125	.119	...
Length of snout	.088	.091	.088	...
Diameter of iris	.035	.037	.029	...

Meristic characters

Character	Locality and number of specimens				
	Gulf and Caribbean (7)	Sierra Leone (1)	Canary Islands (1)	Liberia (1)	Dakar (142)
First dorsal spines	17–18	16	16	17	...
Dorsal finlets	8–9	9	9	8	7–9
Anal finlets	8–9	9	8	8	7–9
Upper gillrakers	2–3	2–3	3	4	...
Lower gillrakers	9–11	9–10	9–10	12	...

* One Gulf of Mexico specimen much deeper than all the others was omitted.

† Average for June and October specimens. January specimens were much deeper and were believed to constitute a different population.

Acanthocybium solandri (Cuvier and Valenciennes): The capture of a wahoo about 240 miles southwest of the Cape Verde Islands (observation 41; Pl. I) may afford new data on the distribution of this species. While it is common in the western Atlantic and in the

Caribbean, and a single capture has been reported from the Mediterranean, we have been unable to find any mention of wahoo from the Atlantic coast of Africa or the offshore islands. Tortonese (1939), in tabulating the worldwide distribution of the scombrids of the Mediterranean, excluded this species from the eastern Atlantic. This record shows that the species ranges well into the eastern part of the equatorial Atlantic.

The comprehensive lists of the fishes of Brazil compiled by Ribeiro (1918) and by Fowler (1941), as well as Tortonese's additions (1948) to the latter, do not include the wahoo. On the basis of three captures in the Guiana current area (observations 42–44), and of specimens seen by us in the markets of Recife, we can state positively that the wahoo is not uncommon off northern Brazil. Wahoo were taken in waters whose surface temperature ranged from 74.1° to 83.1° F.

Gempylus serpens Cuvier and Valenciennes: The taking of a snake mackerel on hook and line appears to be an unusual event. This one took a whole squid trolled at night (observation 45; Pl. II).

Makaira nigricans ampla (Poey): While marlins are frequently taken in the offshore waters of the Pacific by tuna fishermen using long lines, there is no corresponding fishery to provide information on their distribution in the Atlantic. The offshore capture of a blue marlin (observation 46; Pl. II) may therefore be of interest.

Seriola falcata Cuvier and Valenciennes: The falcate amberjack (Ginsburg, 1952), is especially abundant in Bermuda waters. The individual taken (observation 47) was caught close to St. David's Head and may be considered as belonging to the local fauna rather than to that of the open ocean.

Coryphaena hippurus Linnaeus: As the common dolphin is known to be widely distributed over the tropical oceans, it is not surprising that 8 of these fish were taken and about 120 more were sighted. They occurred over a very wide geographical range, but were not found in waters whose surface temperature was below 70° F. In the plankton-rich but relatively cold waters of area II off the African coast the dolphin was not found, although scombrids were hooked fairly frequently. This is in keeping with the findings of Postel (1950), who reported that the dolphin was a rare fish on the West African coast, occurring only in the warm season and not in large schools. The dolphin was the only large pelagic fish other than sharks taken or seen in the offshore waters of area I, but was more abundant in area III.

Coryphaena equisetis Linnaeus: The less common little dolphin was taken on three occasions (observations 58–60) at widely separated offshore locations. It was found only in waters of area III whose surface temperature exceeded 75° F.

Unidentified fishes: In a number of instances, unidentified fishes were either hooked and lost or merely observed from aboard ship. Fish whose size is estimated as "large" were those which damaged heavy trolling gear. As gear which held a 162 cm. wahoo was parted on two occasions (observation 76), we can get some idea of the minimum size of these fish. Since our "large" fish struck at artificial lures being trolled at rather high speeds, tunas or very large wahoos would seem to be by far the most probable species.

Three separate attacks on scientific gear were made by unidentified marine animals. Because of the nature of the damage, the size of the animals must be estimated as large. At 2°21′N, 34°12′W, a bathythermograph was struck when at a depth of 695 feet in 2000 fm. of water. The fins on the tail of the instrument were deformed, but no scratches or tooth marks were evident. On two different occasions on the same day at approximately 13°00′N, 55°25′W, electrodes encased in a formica-canvas composition ⅜″ thick were attacked and destroyed. These electrodes were being towed well astern on 1000 lb. test cable at an estimated depth of 15 feet. When retrieved, one case was found to have been broken in half and the other showed deeply gouged tooth marks. At the time of these attacks the ship was making 12 knots.

THE OBSERVATIONS CONSIDERED BY AREAS

Table III summarizes the observations according to areas and species. Area I seems by far the poorest. The falcate amberjack and blackfin tuna appear to belong to the local fauna of Bermuda rather than to that of the oceanic area. Thus the common dolphin was the only fish of any value taken or seen in the offshore waters. Four unidentified fish were lost in this area, and two of these were considered to be large. The fishing was not notably better in May and June than it was in the winter months.

Area II is quite rich in scombrid fishes. Four valuable species were taken, and another, the little tuna, or false albacore, *Euthynnus alletteratus* (Rafinesque) was seen in quantity at the Dakar markets. Dolphin, however, were not observed in the area either in winter or summer. The fishing, especially for the yellowfin tuna, appeared to be better in the summer than in the winter. This species was taken all along the West African coast from Port-Étienne to Freetown in the summer, and may well have accounted for gear damage sustained in the same area in the winter.

Area III produced the most fish and also the greatest variety of species. Seven species of scombrids were taken, and three of these, the yellowfin tuna, the skipjack, and the wahoo, were found in the deep offshore waters. The dolphins were also encountered frequently in the oceanic portions of the area. A total of 15 species was identified and at least two others were sighted. Seven unidentified fish were hooked and lost, and four of these appeared to be very large. The three attacks on scientific instruments also occurred in this area. The offshore shoals and islands usually showed evidences of good fishing, and the Guiana current seems to be a likely place for the larger game fish.

The data are rather meager for statistical treatment. We can estimate the trolling times for ATLANTIS cruises 151 and 178 only. To attempt to roughly assess the potentialities of the areas, we have considered only the scombrid fishes and dolphins, as the other species are either of no sport or commercial value or are not apt to occur pelagically in important numbers. Unidentified fishes which were hooked while trolling are included, as it seems very probable that they were either dolphins or scombrids. On this basis, we found that about 70 hours of trolling were required to hook a fish in area I, about 17 hours in area II, and about 15 hours in area III. If only the catches made in water over 100 fathoms deep are considered, the respective figures are approximately 94 hours for area I, 21 hours for area II, and 30 hours for area III. While it is recognized that the data are insufficient to afford a definitive comparison,

TABLE III

SPECIES OBSERVED IN EACH AREA

Figures in parentheses are estimates

Species	Number caught	Number lost	Number sighted
AREA I			
Carcharhinus longimanus	1	1	. .
Unidentified shark	. .	. .	2
*Parathunnus atlanticus**	1	. .	. .
*Seriola falcata**	1	. .	. .
Coryphaena hippurus	4	. .	(50)
Coryphaena sp.	. .	. .	1–2
Unidentified triggerfish	(10)	. .	(100)
AREA II			
Carcharhinus longimanus	1	. .	. .
Unidentified shark	. .	. .	1
Katsuwonus pelamis	2	5	. .
Neothunnus albacares	6	. .	. .
Thunnus thynnus	1	. .	. .
Thunnus sp.	. .	1	. .
*Sarda sarda**	1	. .	. .
Unidentified fish*	. .	2	. .
AREA III			
Prionace glauca	2	. .	. .
Carcharhinus longimanus	14	3	(10)
Sphyraena barracuda	2	. .	. .
Katsuwonus pelamis	1	. .	. .
*Euthynnus alletteratus**	2	. .	. .
Neothunnus albacares	4	1	(1600)
*Parathunnus atlanticus**	6	1	. .
*Scomberomorus maculatus**	1	. .	. .
*Scomberomorus cavalla**	1	. .	. .
Acanthocybium solandri	4	. .	. .
Gempylus serpens	1	. .	. .
Makaira nigricans ampla	1	. .	. .
Corphaena hippurus	4	1	(117)
Coryphaena equisetis	8	. .	. .
Coryphaena sp.	. .	. .	1
Unidentified triggerfish	. .	. .	(20)
Mola mola	. .	. .	1
Unidentified fish	. .	7	Many

* These species were found only in shoal water.

this rough statistical presentation tends to confirm our previous estimates about the relative productivity of these areas.

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Contribution No. 652

A COMPARISON OF CERTAIN NORTH ATLANTIC WIND, TIDE GAUGE AND CURRENT DATA[1]

By

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ABSTRACT

Wind components from large areas within the zones of the trades and westerlies of the North Atlantic Ocean are determined by means of a geostrophic template and mean weather maps. These wind speeds are compared with current speed data from the trade-wind zone as well as the Gulf Stream and to tide gauge data from Bermuda-Charleston, Galveston, and Miami. In long-term averages, the trade winds undergo monthly fluctuations which are similar to those of the current speeds. The monthly fluctuations of the trades plus westerlies are similar to those of sea level slope between Bermuda and Charleston and to those of sea level height at Galveston. While short-period average winds may be measured easily by the template method, their correlation with the corresponding current and tide gauge data is relatively poor.

INTRODUCTION

Oceanographers have long sought means of using data collected in related fields to supplement the observations obtained on oceanographic cruises. Data on winds and on heights of sea level have been suggested for this purpose, and certainly the low cost of obtaining such data plus the fact that they are continuous for long periods make such an idea attractive. The studies of Montgomery (1938), Iselin (1940) and Fuglister (1951) are pertinent. More knowledge of the relationships between winds, sea level heights and hydrographic events is needed, and it is with the hope of adding to the present understanding that this paper is written.

WINDS, CURRENTS AND MEAN SEA LEVEL

In a mathematical treatment, Munk (1950) has shown that a circulatory current system, such as the North Atlantic eddy, responds to the curl of the wind stress acting upon it. Similarly, Stommel (1951) and Hidaka (1952) have used the stress of both the trades and the westerlies in explaining features of oceanic circulations.

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For the actual ocean, it has not been established that the major currents are totally dependent upon the winds. Clearly the winds do exert an influence, but there remains the possibility of a direct contribution to current from the earth's heat budget and consequent thermal distribution.

The density distribution which is normally associated with an ocean current is reflected in the slope of sea level across the current, and, in the absence of other influences, two suitably located tide gauges could record this slope. In actuality, other influences, such as atmospheric pressure and local winds, have an independent effect and the distances of the gauges from the edges of the current allow for heights not identical with those at the edges.

DATA

The tide gauge data used here were obtained from U. S. Coast and Geodetic Survey records and from a comprehensive compilation of records gathered by Walter H. Munk of Scripps Institution of Oceanography. The data have been corrected for atmospheric pressure. The current data are based on U. S. Navy Hydrographic Office (1946) charts.

The normal pressure maps and monthly mean pressure charts of the U. S. Weather Bureau (1946, 1943) are the sources of the long- and short-period wind values. The geostrophic template used in conjunction with the maps is shown in Fig. 1.

LONG-TIME MONTHLY AVERAGES

Fuglister's (1951) values for observed and calculated (harmonic analysis) current speeds for his segment 1 (trades) are shown at the top of Fig. 2. The calculated values have been included because of the paucity of observed values in this segment. The next curve in Fig. 2 shows the template-measured trade winds. The outstanding feature in each of these three curves is the July maximum. Slight fall and spring minima and a winter maximum are also present. Fuglister found similar seasonal fluctuations in wind components from an area near the segment. It is interesting that the template-measured trades, which represent a much larger area, agree as well with the current as do the more local winds of Fuglister. This agreement of wind and current fluctuations does not preclude a direct contribution to current from the earth's thermal distribution.

The next curve in Fig. 2 gives the northbound components of current for an area covering four degrees of latitude from the U. S. coast

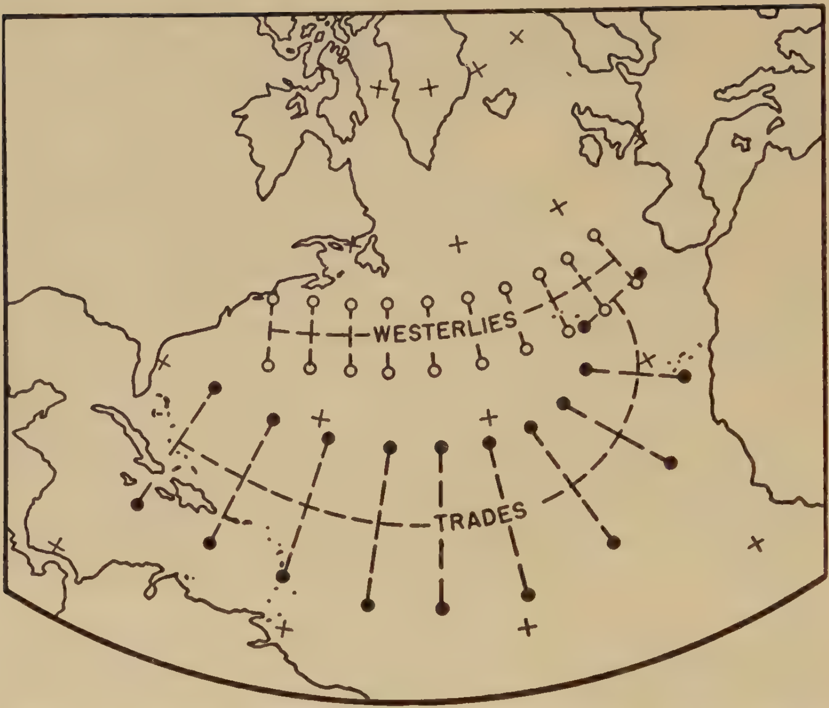

Figure 1. Geostrophic template for measuring wind components at 10 pairs of points in the trades and at 10 pairs in the westerlies. The distance between any pair of points is inversely proportional to the sine of their mean latitude. Components are expressed in terms of millibars of pressure difference.

to the neighborhood of Bermuda. It is remarkably similar to the trades curves.

The much greater current speeds of the Gulf Stream are shown by Fuglister's observed values (bottom curve of Fig. 2) for his segment 4, located just south of Cape Hatteras. In its main features, this curve resembles the preceding ones. It has a large maximum extending from June through August and a small January peak. Here the minima are in February and November, while those of the trades are in April and September through October.

The values of these last two curves in Fig. 2 show no systematic tendency to lag behind those of the trades currents and winds, although they represent areas much farther downstream. With regard to the similarity of the seasonal variations in wind and current speeds, it is noteworthy that the westerlies, which may be considered part of the system, have not been considered.

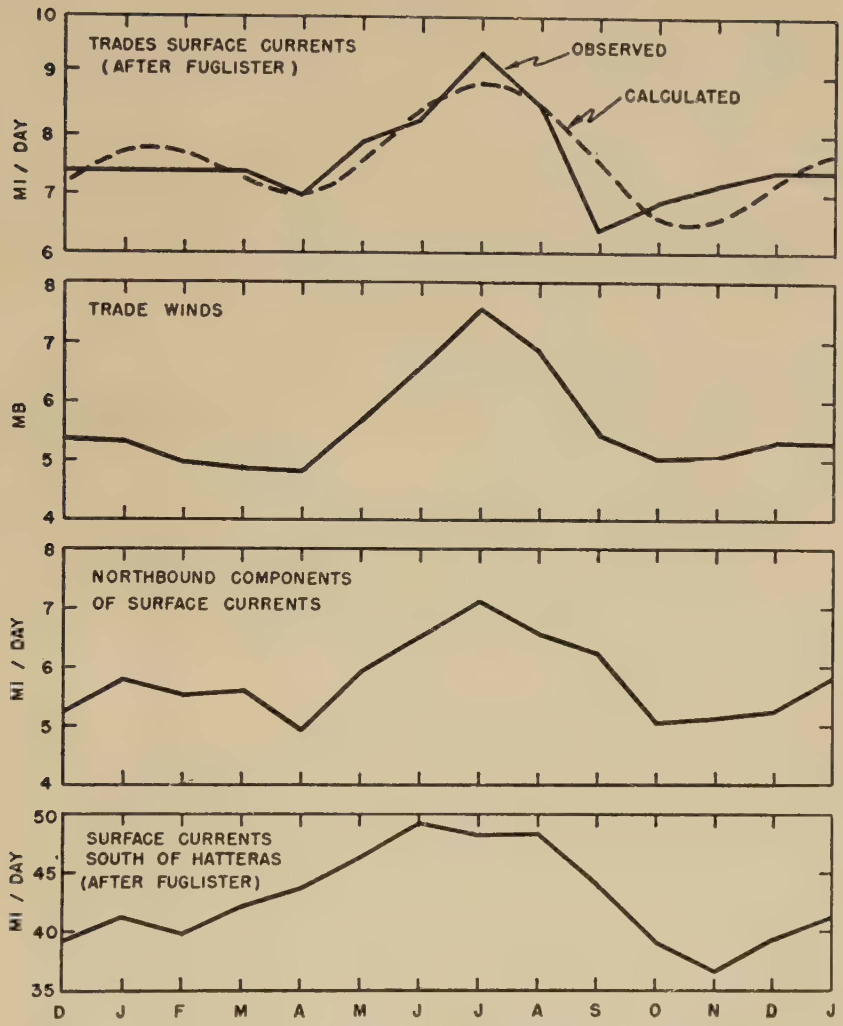

Figure 2. Long-time monthly averages of trades surface currents, template trade wind components, northbound components of surface current for an area extending from the southeast coast of the United States to Bermuda, and surface currents in the Gulf Stream south of Cape Hatteras.

For the westerlies, the template yields a W-shaped curve (Fig. 3), with maxima in January and July and minima in April and September. The rapid decline between July and September closely matches that of the observed trades currents. There is some question here as to

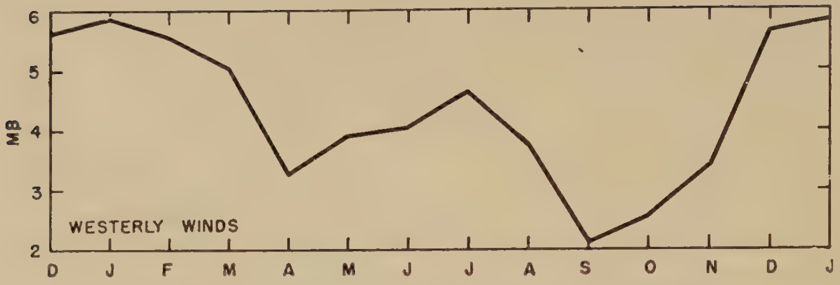

Figure 3. Long-time average monthly west wind components.

the significance of the January maximum because of the gap in the template along the southeast coast of the United States. In an annual average, there is little resultant wind in this area, but seasonally there is a decided shift of resultant wind direction from northerly in winter to southerly in summer. A westerlies template extended southwestward to measure components parallel to the coast would therefore yield lower average values in winter and consequently a curve that would be in closer agreement with the trades.

The effect of the gap is still visible when the trades and westerlies are added to give the values shown in the uppermost curve of Fig. 4. The winter maximum, though less pronounced, is still large enough to be out of line with the winter trades values.

The second curve in Fig. 4 gives the relative slope of sea level between Bermuda and Charleston. It closely resembles the previous curve and therefore shows similar disagreement with the trades in winter. These high winter values may be due to the lowering of sea level at Charleston in response to offshore winds. A tabulation of the percentage frequency of the various wind directions at Charleston for the years 1931–1938 shows that offshore directions are more frequent in the period September through February while the wind stress data of Cochran and Osborn (1950) show a net offshore stress from October through April.

The curve for the height of sea level at Galveston (third curve in Fig. 4) resembles the two previous curves remarkably well, especially in view of the distance from the Gulf Stream. It has a larger amplitude and its spring maximum and summer minimum occur somewhat later. As at Charleston, offshore winds are more frequent in winter.

At Miami the fluctuations in sea level (bottom curve of Fig. 4) show some agreement with the preceding values. Because of the large range, the scale has been halved. The fall maximum is somewhat late, and in the period from March through June the sea level is

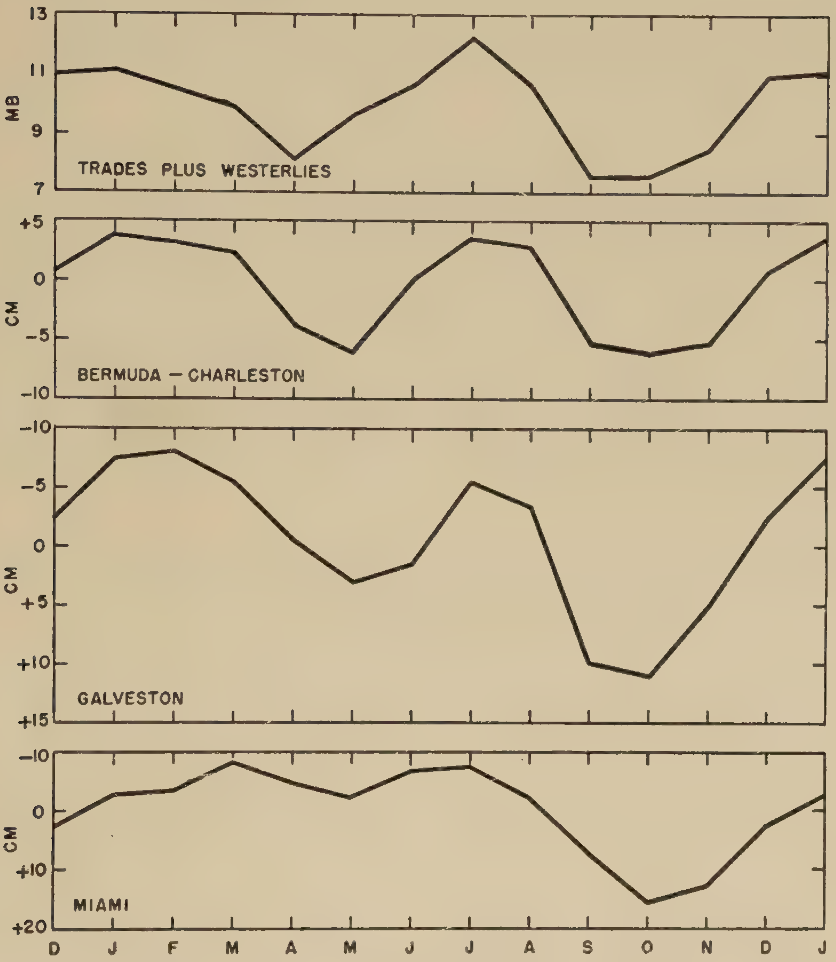

Figure 4. Long-time averages for trades plus westerlies, the relative slope of sea level between Bermuda and Charleston, the height of sea level at Galveston, and the same at Miami. The zero points for the tide gauge height scales were arbitrarily chosen.

too low. Compared to the trades, sea level is too low from December through June. U. S. Weather Bureau (1938) charts indicate a weaker onshore wind component in winter and spring.

It is interesting that the four curves in Fig. 4, representing different factors in different areas, should be so similar. Of greater importance, perhaps, is the possibility that, after consideration of the coastal winds, all of the curves will have essentially the same shape as those for the trades. A quantitative analysis of the effects of these winds, though necessary to a full understanding of the curves, is beyond the scope of this paper.

SHORT-TIME AVERAGES

Fig. 5 shows three-month running means of trades plus westerlies, the Bermuda-Charleston slope, the height of sea level at Galveston, and the same at Miami. The agreement between the seasonal variations of these values is much poorer than it was in the case of the long-time averages. Yet the main peaks and valleys do show a reasonable correspondence. At Miami the spring values tend to be too low, and in the fall there are lags in the curve; at Galveston there are lags in the curve in spring and summer. These tendencies are in line with the long-time relationships. The Bermuda-Charleston values in this case have as large a range as do those of Galveston and Miami. For averages of periods shorter than three months, the agreements are negligible.

Three-month averages for the trades (not shown) were compared with the above values. The fluctuations in the trades followed those of the other data fairly well in certain periods but not in others. The expected low winter values did not always appear.

The Iselin (1940) Gulf Stream transport data (not shown) were also examined. Compared with the trades, the trades plus westerlies, and the Galveston data, they show no better than fair agreement. The transport figures have a tendency to lag one to three months behind the other data. This may be due to a slower response of the deeper currents to the influence of wind. The Bermuda data are incomplete for this period. Iselin showed good agreement with sea level at Miami and Charleston.

No one- or two-year lags have been noted in any of the above data.

The lesser agreement of the short-time data suggests the influence of extraneous variables whose net effect is less in long-period averages. The more important variables may be: (a) The amount of water entering the system from the South Atlantic and from the coastal waters to the north of the Gulf Stream. (b) The local winds affecting sea level at the tide gauges. (c) Temporary time lags. (d) The migration of average pressure centers across the westerlies section of the template.

Those of lesser importance may be: (e) The ratio of geostrophic wind to sea level stress. (f) The deeper currents. (g) Rainfall and runoff in the vicinity of the tide gauges.

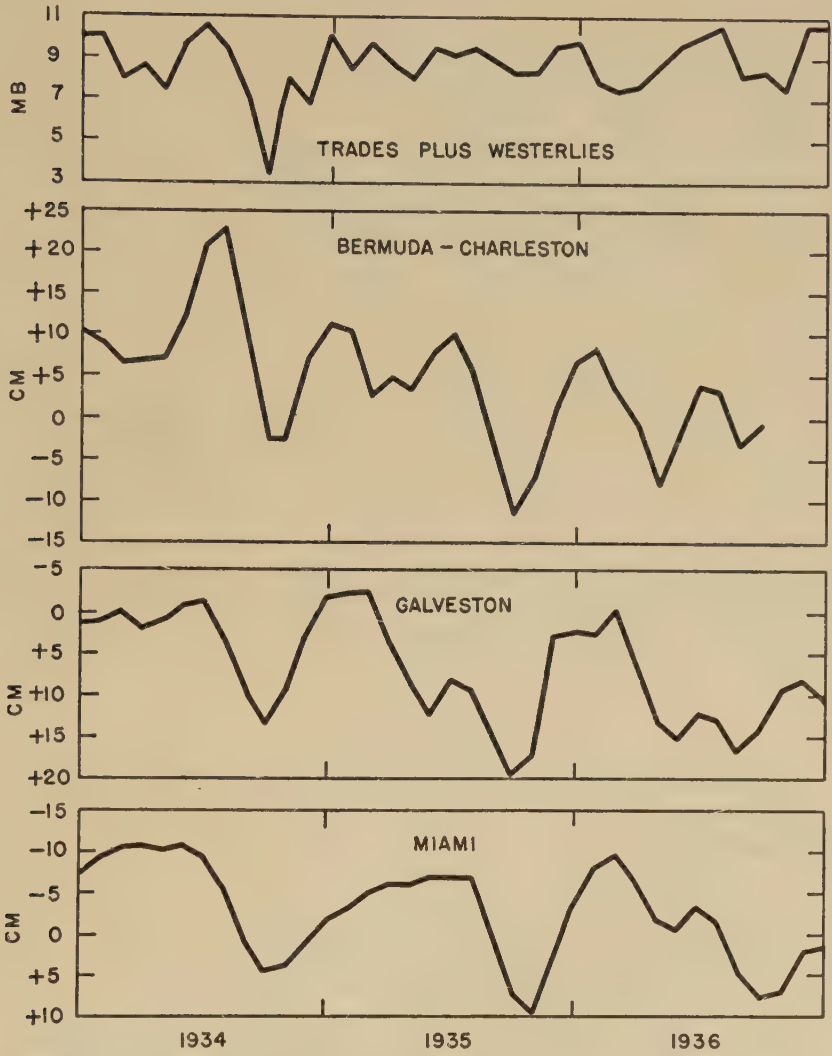

Figure 5. Three-month averages for trades plus westerlies, the relative slope of sea leve between Bermuda and Charleston, the height of sea level at Galveston, and that at Miami. The zero points for the tide gauge height scales were arbitrarily chosen.

Special studies of each of these variables may be necessary to a complete understanding of the relationships between winds, tide gauge readings, and currents.

CONCLUSIONS

1. The trade winds (measured by the template method) and the surface currents for an area in the trades zone and for an area off the southeast coast of the United States have similar seasonal fluctuations in long-time monthly averages. In three-month running averages (short period) the agreement of trade wind fluctuations with those of the best available transport data is only fair.

2. The seasonal variation of trades plus westerlies agrees very well in long-time averages and fairly well in three-month running averages with variations in the: (a) Relative Bermuda-Charleston sea level slope; (b) height of sea level at Galveston; (c) height of sea level at Miami from July through February.

3. Adjustments for the influence of local winds at the tide gauges and an extension of the westerlies template along the southeast coast of the United States would result in closer agreement in the long-time averages between the seasonal variations of 2 (above) and those of the trades.

4. A better understanding of the significance of current speed fluctuations, tide gauge values and wind values depends on a study of the effect of extraneous variables and on the availability of a long continuous record of Gulf Stream transport and surface current observations for use as a standard.

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TURSIOPS AS AN EXPERIMENTAL SUBJECT

BY BARBARA LAWRENCE AND WILLIAM E. SCHEVILL

During some recent acoustic experiments at Marine Studios in northern Florida, the authors were struck by the learning ability and behavior of their subject, a *Tursiops truncatus* (Montagu). There is a certain amount of published evidence (Wyman, 1863: 611; McBride & Hebb, 1948; McBride & Kritzler, 1951; Kritzler, 1952) suggesting that small odontocetes are truly remarkable animals, not only in their aquatic adaptations, but also in their intelligence. Observations over a period of years of Mr. Adolf Frohn's remarkable work with the Marine Studios' performing *Tursiops*, "Flippy," confirm this. Nevertheless, as far as we have been able to find out, a porpoise had never before been used as a subject in a conditioned response test. For this reason, the details of our animal's behavior during her conditioning or learning period seem of particular interest. Our experiment, which was designed to explore the upper frequencies to which a *Tursiops* responds, is reported on elsewhere (Schevill and Lawrence, 1953*a*, *b*). In this paper we are concerned with the reactions of an adult bottlenosed porpoise, which, four weeks after she was caught and six days after intensive training was started, was taking dead fish from the hand instead of hunting live prey. For our purposes, hand feeding seemed the swiftest and most practical way to get assessable responses. Our training was in no sense intended to show what or how fast a *Tursiops* could learn. It was designed to establish a means of determining whether or not our subject had heard a signal. In other words we wished her to learn as swiftly as possible to respond to an acoustic signal of known but variable frequency, and we wished her never to act in the same way in the absence of our signal. Our training, though successful in producing the desired data, was less so in eliminating independent actions, and the sum total of the animal's behavior during the conditioning period makes a most interesting picture of the alertness of a propoise, as well as the ease with which it could be tamed and taught.

LEARNING

Our subject was a female, apparently old as indicated by the wear of her teeth; she was 252 cm. long and, at the end of our experiment when she was a little thin, weighed 148 kg. She was shy, gentle, not very curious, easily upset, and often unpredictable. When caught she was accompanied by two young of about the same age, a female still nursing and a male that was not. After three weeks of captivity in a tank, when she had learned to eat dead fish and occasionally to accept one from the hand of the feeder, she was turned loose in a fenced-off inlet of the Matanzas River at Marine Studios. This was an enclosure about 55 meters long and 20 wide with the long axis east and west. It was mud bottomed and fairly shallow, the deepest part having only eight feet at low tide. Visibility was poor; the water was generally so turbid that even a white object could not be seen through it for a greater distance than 0.3 m., making it extremely difficult to keep track of our animal's activities. There was considerable underwater noise, mostly made by snapping shrimp. Food fish, chiefly mullet, were present. Here she reverted to a semi-wild state, her only contact with people being the fish that were thrown to her at irregular intervals from the north bank. When we started work with her a week after she was put here, she was extremely wary, especially of our rowboat, possibly associating it with the nets in which she was captured, and also of a platform that had been built at the southwest corner of the pool during her sojourn there. Overcoming her aversion to this platform, which was to be used as a feeding station, was a critical part of her training. Our initial efforts to establish contact with her were entirely unsuccessful. The size of the enclosure permitted her to keep her distance, and on the first day she was far too upset to do anything but swim excitedly from one end of the pool to the other, staying as far away as possible from our rowboat and the platform, and absolutely refusing to pay any attention to fish even when they were thrown close to her. Whole dead butterfish (*Poronotus triacanthus*) were used for feeding and training her, and these made a slap on the water which she later showed us she could hear for a considerable distance. She was kept on short rations of 12–15 pounds a day instead of a more normal 18–20, the fish averaging about five to a pound.

On the second day, when we fed her from the bank at three different times, it was possible to get her to take fish if they were thrown near enough for her to see them through the murky water before they settled to the bottom. This was not easy, for she still avoided us. By throwing each of a series a little in front of the previous one we could coax her towards the platform. She never stayed there, however, but always returned hastily to the head of the inlet to circle. This was a favorite loafing place of hers, perhaps because the deeper water was cooler than in the rest of the enclosure. On the third day we gave her four feedings. When one of us was out in the rowboat at the east end of the inlet, she stayed down at the west end, and it was not hard to coax her over to within 20 feet of the platform. At such times she always came up to blow on the far side of the inlet and approached the platform swimming as deep as she could. This meant that at high tide she made no surface wave, so that often the only traces of her presence were the slicks that she made in turning after taking a fish we had thrown. This keeping out of sight and away from us was in marked contrast to her apparent curiosity when she repeatedly blew quite near some children on the bank, eyeing them as she did so.

By the fourth day she was much more accustomed to us and the platform, coming closer to get her fish and departing less hastily. She had also shown that she associated the sound of the fish slapping on the water with being fed. We tested this a number of times by slapping the water without throwing the fish when she was too far away to see, and found that she would come immediately. When she was near, the fish was tossed to her. After she had learned to come for this sound, we hung a length of two-inch iron pipe in the water, called her with the slap, and then banged the pipe with a hammer as she was about to take the fish. The difficulty of seeing what she was doing and where she was going led us in the beginning to call her only when we felt fairly sure she would respond, and to wait until she was close before we banged the pipe. The sound never frightened her away, and she soon learned what it meant. Up to this stage of her training she learned quickly, gradually became tamer, and showed no confusion, so on the fifth day we tried to double the number of conditioning feedings by using half fish. First we interspersed half with whole fish and felt that she was taking them, although she was too deep for us to see whether or not she was spitting them out after seizing them. Later in the day when we tried half fish only, she apparently took a few of these and then lost all interest. About three times she came close enough to see them, but turned away without taking them; then she ignored the signal, even refusing to come for whole fish. This was our first evidence of either confusion or lack of cooperation on her part. Porpoises, "Flippy" for example, have been taught to eat pieces of fish, and in a smaller enclosure with more time it might have been possible to do so with her. However, as this was not essential to our work, we gave up the attempt.

On the sixth day we resumed using whole fish, which she took eagerly at our first signal. After this we fed her nearer and nearer to the end of the platform, waiting until she was very close before easing the fish into the water just beyond arm's length. This was in an effort to make her come near the surface where she could see us as she seized the fish. We felt that if we could overcome her shyness to this extent, it would be easy to persuade her to take fish from the hand. By this time she was much calmer; although she never lingered, she was much more leisurely about turning away after taking her fish. She had become accustomed to the platform and the rowboat, both with and without people, and her blowing, even near the platform with people on it, was much less explosive than before (this explosive blowing seemed to have much the same meaning as a horse's snorting). She still spent most of her time circling in the far, deep end, but occasionally made trips to the nearer end, sometimes coming fairly close to the platform, apparently prospecting (by "prospecting" we mean an uninvited, independent visit to the feeding station in the absence of an acoustic signal). By the seventh day she was coming to within two feet of the platform, perfectly visible when she took the fish, and not scared of the feeder's hand. The next step was to persuade her to take fish from the fingers, which she did on the first try, without hesitating, but hastily, and swirling away fast. She repeated the performance three or four times with no refusals, and quickly became accustomed to it, coming in less deep and departing less fast. Up to this point we had signaled only when she was not too far off. Now we tried calling her with the pipe regardless of her position. This was successful in bringing her from anywhere in the pool, no matter which way she was heading. After it was thus clear that she understood our signal, we tried to call her only when we felt sure she had no intention of coming on her own. Her pattern of approach when she did come in to be fed was to swim within eight or nine feet of the fish, turn on her side and come the rest of the way moving her head with a nodding motion, to all appearances looking for the fish as she came. She judged her distance nicely, never coming closer than she had to, so that the fish was in front of and above her as she took it, whereupon she would go off, righting herself as she swam away. She never snatched, and never got fingers with the fish, even though the feeder's hand was in the water and the fish were sometimes so small that she nudged the hand as she took them.

By the eighth day it was apparent that she understood our signal perfectly clearly, that we had overcome most of her initial fears, and that she actually preferred taking dead butterfish from the hand to hunting live mullet. When we later substituted a 15 kc note for the pipe signal, she learned its meaning quickly. After two successive feedings at the beginning of each of which we signaled with both pipe and 15 kc note, she had no further difficulty with the new signal. Even when the frequency was varied drastically we never had to teach her its meaning again.

INCIDENTAL BEHAVIOR

As she became tamer, evidences of independent behavior increased, and we were never successful in getting her to desist, partly because too persistent efforts to break up such behavior tended to make her ignore us. She frequently repeated maneuvers that had gained her a fish. If we signaled her to return for a second fish as she swam away after a first, she would next try returning without a signal. If we called her often from a particular place, she would return there after responding to a signal and then come right back without waiting for a second one. Her prospecting trips were often started from spots whence she was customarily called. Such obvious independence was, of course, never rewarded. At other times it was more difficult not to reinforce bad behavior, and, while failure to reward prospecting never made her give it up, failure to respond as she felt we should confused her. That is to say, if we mistook a prospecting trip for a slow response and gave her a fish, such trips immediately became more frequent, but if an apparent prospecting trip was in reality a slow response and she got no fish, her reaction the next time was not to come faster, but sometimes not to come at all. Other things also made her responses erratic. Too persistent attempts on our part to make her come when she had reason to feel sure there were no fish resulted in a refusal to pay any attention. This was especially true in the early morning when, presumably hungry, she spent a certain amount of time hanging about the end of the platform. At these times we never fed her, but waited until she headed away, and then sent her a signal. On such occasions we were rarely successful in getting her to return, as if she thought there could be no fish where she had just looked and found none. This kind of confusion seemed rather obviously to come from efforts on her part to think things out. Later in our work, when she refused to come for signals we knew she could hear, it was less clear what was disturbing her. The first time coincided with the arrival of two speed boats which circled and idled outside her enclosure, and which of course made a lot of underwater noise. Again, early the following morning, when she should have been hungry because of short rations the day before, she still refused to respond except occasionally. Later in the morning she settled down again, responding well and clearly. At other times when she refused to heed signals, she was obviously preoccupied. On occasion she would loaf near the surface, her body arched and head bent down, with her blowhole out of water and often open for longer than the usual breathing time. At these times we could see her turning her head from side to side as if listening or looking at or for something under water. Sometimes she would dash from one end of the enclosure to the other, jumping clear of the water and smacking it with her tail as she dove. The few times we saw her apparently chasing fish, with mullet jumping near her, she behaved much like feeding *Tursiops* seen in Biscayne Bay, swirling around on her side fast and erratically, part of the time with one of her flukes showing (cf. Gunther 1949: 124). At other times she would dive again and again in the same place, often coming up with mud on her snout and back as far as her dorsal fin.

These various activities of hers did not occur at regular intervals. Careful observation showed no well-marked diurnal behavior patterns. Her path when idly circling the pool varied, but on any given occasion stayed the same for quite a time, usually until she was distracted by something else. During these periods she was apt to blow regularly at the same place. When feeding started, especially in the morning after she had been called for her first fish, she always was more excited,—swimming faster, blowing more hastily, and varying her path more. If we then waited a long time without resuming feeding, she would relapse into leisurely circling. The early morning feeding also stimulated more active prospecting on her part, and she would come in fast from any corner of the pool, with or without signal.

Although the murkiness of the water prevented us from seeing her except when she surfaced, we were sometimes helped by indications of her concealed movements. In calm weather or at low tide it was easy to track her when shallow, as she was followed by a conspicuous V-shaped wave, with the initial depression usually about over her nape and the first marked wave crest close behind, nearly over the dorsal fin. A less immediate indication of her movements was given by the slicks or boils caused by the upstroke of her flukes as she swam (cf. Gunther, 1949: 117, 118, 128, 132), and the often more violent swirl resulting from an abrupt change of course.

During this experiment we listened continuously and attentively over a wide range of frequencies, from about .05 to 153 kc (and occasionally as high as 196). Our porpoise not infrequently made sounds, mostly restricting herself to faint creaks. The whistle-like squeal and louder snoring creaks so generally heard from groups of *Tursiops* were almost totally absent. Even during the excitement of being seined out of the pool at the end of the experiment, she made no greater outcry than this gentle creak, and not much of that. The only time when we were able to associate her sounds with behavior or state of mind was on the morning after the motor boat disturbance, when she was still upset; then she seemed to have more to say than usual, sometimes squealing and creaking, but not in any consistent relation to our signal; this was the only occasion on which we heard her give the whistle-like squeals.

Even more noteworthy was the complete absence of any evidence that she was using echo-location, in spite of the murkiness of the water (Secchi disk reading usually 30 cm.), which might seem to call for some such method of navigation. Although she spent most of her time actively swimming about the pool, she was for the most part silent, and such sounds as she did make seemed to have no relation to her movements or surroundings. When she swam in to the platform to get her food we almost never heard sounds from her.

Her gentleness when we started hand feeding confirmed our previous experience with *Tursiops*, when one of us, in a preliminary investigation of breathing and phonation, took considerable liberties with a young bull *Tursiops* (this was "Flippy", then in his first year of schooling). Although the two were together in a small tank, 6 m. in diameter, and the *Tursiops* actively resented being handled, he neither bit nor struck the man with tail or snout in spite of abundant opportunities during the half hour struggle before the porpoise was finally, with the aid of Dr. Henry Kritzler (then Associate Curator at Marine Studios) put into a sling. This gentleness was also shown at Mr. P. F. McKinney's "Theatre of the Sea" on Windley Key, Florida, where two *Tursiops* were not only willing but eager to play with a sixteen-year-old boy, Clarence Lowe, who grabbed them by the dorsal fin to be pulled about or seized them around the snout. This tolerance of people was even more remarkable in our animal, which accepted us so swiftly even though old when caught. It is further noteworthy in view of the not infrequent fractious behavior of individuals in a group of porpoises, which will whack each other audibly with the tail when annoyed, and otherwise play rather roughly. The dominant animals will also threaten with even more audible jaw snaps, threats which are not always idle, as witness the numerous series of tooth marks seen on some individuals. It is also true, as we have reason to know, that it is perfectly possible, though unusual, for an experimenter to exasperate a usually amiable animal into taking a gentle nip at him.

SUMMARY AND DISCUSSION

Although porpoises are familiar to most seafarers, few people have had the opportunity to study them in captivity. Occasional specimens, particularly beluga (*Delphinapterus*), have in the past been kept alive for relatively short periods of time, but observations on them are few (e.g. Wyman, 1863; Lee, 1878; Townsend, 1914). It was not until the late Arthur McBride of Marine Studios successfully developed a system for keeping *Tursiops* alive and healthy that consecutive observations over a long period have been possible. Such observations suggested very strongly that porpoises are of a high order of intelligence, McBride and Hebb (1948: 120) implying that the level lies between that of a dog and a chimpanzee. This is borne out by Mr. Adolf Frohn's successful program of gradually teaching a varied repertory of tricks to a single *Tursiops* at Marine Studios (e.g., Hediger, 1952). In spite of this, actual experiments to see how swiftly a fresh-caught, adult *Tursiops* can be tamed and how readily it learns appear not to have been reported. Incidental to some acoustic experiments, we have recently had occasion to observe such behavior in detail and were interested by the ease with which our animal learned. In order fully to appreciate this, her performance should be considered against the background of her normal habits, her age, and her environment.

Wild porpoises habitually feed on live fish that they actively pursue. Our animal was fed dead ones, which she readily accepted as a substitute in spite of the presence of live fish in her enclosure, and only refused this abnormal diet when we tried feeding her cut fish. The porpoises on exhibition at Marine Studios have also given up hunting live prey, though they frequently chivvy the fish that are in the tank with them. Apparently this is just for fun, as they rely for food on dead fish that are hand fed. Of the two young that were caught with our cow, one, which was not nursing, learned to eat dead fish, while the other, which had not been weaned, would carry them around in her mouth but would not swallow them.

Our animal was apparently old, and by analogy with land mammals this must have been a handicap to her in learning, yet in four days she was trained to come for a fish in response to an acoustic signal, and by the seventh day she had overcome an initial wariness of us and an even more pronounced aversion to the feeding platform to the extent of being willing to approach it closely to accept a fish from the hand. We never had to teach her to take her food gently; from the very beginning she avoided biting the feeder. This has so generally been the case with the exhibition porpoises at Marine Studios and elsewhere that it is more or less taken for granted, and yet it is certainly at variance with the usual behavior of a predator, particularly one that has been in captivity for scarcely a month.

One of the most difficult obstacles in the way of her early training was the fact that the experimenter and the subject were in different environments and thus largely out of contact with each other. Later when she was less shy and had learned the meaning of an acoustic signal, we were still handicapped in our efforts by the fact that the enclosure was large and the water in it murky, so that she was almost entirely invisible except for her brief intervals of blowing. This made it impossible to know most of the time what she was doing, and often where she was; as a result much of what she learned was in spite of what must sometimes have seemed to her very confusing behavior on our part.

Our previous studies and observations of porpoises had led us to expect many of the qualities which our animal showed, particularly her intelligence and her gentle willingness to accept people. Evidences of her intelligence were not limited to the speed with which she understood what it was both safe and profitable for her to do. She also persistently indulged in independent actions that varied with the circumstances in such a way as to strongly suggest that she was trying to anticipate our actions by thinking them out.

As we were measuring acoustic responses, we had ample opportunity to listen to our animal. In our experience solitary porpoises have almost always been taciturn, while groups of them, whether free or in captivity, have been quite voluble. It was thus the more noticeable that our solitary animal was not infrequently heard uttering sounds. We listened to these over a wide band of frequencies and were struck by the complete lack of evidence that she was using any of these for echo-location.

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Museum of Comparative Zoology, Cambridge Massachusetts and Woods Hole Oceanographic Institution, Woods Hole, Massachusetts. *Received May 1, 1953.* [Contribution no. 653 from the Woods Hole Oceanographic Institution]

Contribution No. 654

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SIGHT RECORDS OF THE GRAY GRAMPUS, *GRAMPUS GRISEUS* (CUVIER)

In conversation, Dr. Joseph C. Moore of the Everglades National Park has called my attention to the paucity of western North Atlantic records of *Grampus griseus* (Cuvier). It is likely that this whale is not as rare as this would indicate, much as Major Gavin Maxwell has pointed out on pages 261–265 of his book, HARPOON VENTURE (1952), where he describes the abundance of this species off the west coast of Scotland.

On July 14, 1950, some 200 miles east of Cape Cod, three individuals keeping close beside each other were overtaken and passed, our ship going 14 knots. The grampus were making about half our speed as we passed about 50 yards from them.

On August 20, 1952 we encountered a group of over sixty of these small whales near Lat. 40° 00′ N, Long. 71° 30′ W, some 70 nautical miles south of Block Island; visibility was good, and the sea was glassy with a gentle swell. The grampus, in small bunches of four to six, were swimming actively in a variety of directions, though evidently maintaining a general base course at perhaps five knots speed of advance. They were quite frolicsome, sunfishing, pitchpoling, and often breaching clear, sometimes in clean arcuate leaps like porpoises, sometimes falling back head up like a humpback whale. Occasionally one waved the posterior third of the body in the air, again like a humpback. Their closest approach to the ship was about 75 yards, but when we pulled away from the vessel in a dory, they were less shy, passing under us at a depth of about ten feet. They appeared to be in constant vocal communication with each other; a phonographic recording of these rather faint underwater calls was made.

A week later our ship reported a similar encounter some 30 miles further east; there seems little doubt that it was the same species.

Field marks for this form include the high slender dorsal fin, somewhat reminiscent of a killer's, the pale gleam of the back in front of the fin, the rather blunt snout (not as bluff as *Globicephala*), the slender tail with lunate flukes (rather like that of *Delphinus*), which may be seen if the animal breaches. On close approach the characteristic scratch-like markings may be seen. The flipper was not often conspicuous.

As usual with cetaceans, many of the published figures are misleading. Reliable pictures of *Grampus griseus* (Cuvier) are those of W. H. Flower (1872, Trans. Zool. Soc. London, 8, Plate 1) and J. Richard (1936, Resultats Campagnes Scient. Monaco, 94, Plates 6, 7), as well as the characteristic field photographs published by Maxwell (1952, HARPOON VENTURE, Figures 77–82).

Although there has lately been a tendency to refer this species to *Grampidelphis* Iredale & Troughton 1933 (Rec. Austral. Mus., 19: 28–35), I have followed the older custom of using *Grampus* Gray 1828 (in which it was the first species included) because the use of *Grampidelphis* involves acceptance of a conjectural manipulation of an anonymous erroneous type designation of an imaginary species (1829, Zool. Jour., 4: 497), which was ignored as irrelevant for 104 years, only then to be ascribed to a non-binomial author and interpreted as making *Grampus* Gray applicable to the killer whale. Since this type designation is invalid, *Grampus* Gray remains available for *griseus* Cuvier, and does not belong to the killer whale. As long ago as 1862, *Delphinus griseus* G. Cuvier 1812 was designated as the type species of *Grampus* Gray 1828 by J. Reinhardt (Overs. Kong. Danske Vid. Selsk. Forh., 1862, pages 107, 148). For details see the original references and J. R. Ellerman & T. C. S. Morrison-Scott (CHECKLIST OF PALAEARCTIC AND INDIAN MAMMALS, British Museum (N. H.), 1951, pages 739–741), as well as F. C. Fraser (Ann. Mag. Nat. Hist., (12), 4: 942–944, 1951), who reminds us that *Delphinus ventricosus* Lacépède 1804 was founded on a good figure of *Phocoena phocoena* and so cannot be applied to any *Globicephala*, let alone *G. melaena* (Traill) 1809. This synonymy was also pointed out by Thomas Bell in 1837 on pages 481–482 of his popular work, A HISTORY OF BRITISH QUADRUPEDS.—WILLIAM E. SCHEVILL, *Woods Hole Oceanographic Institution, Woods Hole, Massachusetts. Received December 8, 1952.*

[Contribution 654 from the Woods Hole Oceanographic Institution]

Contribution No. 657

BREVIORA

Museum of Comparative Zoology

CAMBRIDGE, MASS. JANUARY 27, 1954 NUMBER 24

A NEW FAMILY, A NEW GENUS, AND TWO NEW SPECIES OF BATOID FISHES FROM THE GULF OF MEXICO

By Henry B. Bigelow
and
William C. Schroeder[1]

The West Indian-Gulf of Mexican region is proverbially poor in skates as compared with the more northerly coastal waters of the Atlantic; so much so, indeed, that two specimens only, of *Raja akleyi* Garman 1881, from the Yucatan Bank and nearby, were the only skates that had been reported in scientific literature from any part of the Gulf prior to 1921. This is fewer than one is likely to find, stranded, along the beaches of Cape Cod during an hour's stroll on any summer day. And while a second species, *R. texana* Chandler 1921, is now known to occur in some numbers around the northern shores of the Gulf from Florida to Texas, it was not until the winter and spring of 1938–1939 that the trawling campaigns of ATLANTIS brought to light the presence of a varied skate fauna at depths greater than 200 fathoms around the coasts of Cuba.

Examination of these, of collections of skates in the U. S. National Museum that had been taken by the ALBATROSS many years ago, and of others taken recently by OREGON of the U. S. Fish and Wildlife Service, had brought to light ten new skates of the genera *Raja*, *Breviraja* and *Cruriraja*,[2] up to 1950, from Cuban waters and from the northern part of the Gulf; also of a new genus, *Springeria* Bigelow and

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[1] Contribution No. 657 from the Woods Hole Oceanographic Institution.

[2] These are *Raja lentiginosa* Bigelow and Schroeder 1951; *R. olseni* Bigelow and Schroeder 1951; *R. teevani* Bigelow and Schroeder 1951; *Breviraja atripinna* Bigelow and Schroeder 1950; *B. colesi* Bigelow and Schroeder 1948; *B. cubensis* Bigelow and Schroeder 1950; *B. sinusmexicanus* Bigelow and Schroeder 1950; *B. yucatanensis* Bigelow and Schroeder 1950; *Cruriraja atlantis* Bigelow and Schroeder 1948 and *C. poeyi* Bigelow and Schroeder 1948.

Schroeder 1951, representing the little known family Anacanthobatidae.

We can now report the capture by OREGON of another new *Raja* from the northern part of the Gulf, and of a skate-like fish, from the southern part, for which a new family seems needed.

Family PSEUDORAJIDAE, Fam. Nov.

Family characters. Rajoidea without dorsal fins; with well developed caudal fin extending around tip of tail and forward along lower side of tail about as far as along upper side, supported by a great number of very slender ray-like strands, apparently cartilaginous;[1] with outer-posterior margins of pelvic fins nearly straight, or even slightly convex if spread widely; anterior wall of spiracle with a transverse row of low vertical ridges, representing the vestiges of the embryonic gill filaments; pelvis with transverse element nearly straight, each of its outer corners with a short projection directed forward.

The batoid fish, described below as *Pseudoraja fischeri,* falls clearly among the Rajoidea because of the shape of its pelvis and of the persistence of vestiges of the embryonic gill filaments on the anterior wall of its spiracles (mentioned above). It is rajoid, too, in general appearance; in the nature of its dermal armature; and in the fact that its snout terminates in a fleshy process, for a corresponding structure tips the snout in the rajoid family Anacanthobatidae, represented in the Gulf of Mexico by the genus *Springeria* Bigelow and Schroeder 1951, and perhaps in the skate *Psammobatis mira*(Garman)1877[2] but is not known to occur in any of the Myliobatoidea. The presence of a rostral projection (albeit a short one) from the front of its cranium, and its lack of a tail spine, point toward a rajoid rather than a myliobatoid relationship, though neither of these two features is strictly alternative, between the two suborders, for a few rajoids lack the rostral cartilage, while it is a matter of common knowledge that some myliobatoids lack the tail spine.

On the other hand, a myliobatoid relationship, rather than a rajoid, is suggested for *Pseudoraja*, superficially, by the shape of its pelvic fins with straight or slightly convex outer contour, and by the large size and the shape of its caudal fin. But, again, we are dealing with characters that are not as strictly alternative as seemed once to be the case. Thus the pelvics of *Pseudoraja* are approached closely, in shape, by those of *Sympterygia* (undoubtedly a rajid) in which they are so weakly concave in outline, when spread, that they can hardly be characterized as "bilobed".[1] And while the caudal fin is a close counterpart, in size and shape, of the caudals of the myliobatoid family Urolophidae, it is similar in shape in the rajid genus *Springeria* Bigelow and Schroeder 1951, though smaller.

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[1] The caudal fin-folds of various species of *Raja*, that we have examined under the microscope, are supported similarly.

[2] Garman (Proc. Boston Soc. Nat. Hist., Vol. 19, 1877, p. 207) described the snout of *mira* as terminating in an "acute point", which is pictured as prickly in his classic monograph (Mem. Mus. Comp. Zool., Vol. 36, 1913, Pl. 27, Figs. 3-5).

With *Sympterygia* and *Pseudoraja* wholly bridging the gap, in shape of pelvic fins, between the typical Rajoidea in which these are definitely bilobed, and the Myliobatoidea, in all of which their outer contour is continuously convex, it is evident that the precise shape of these fins must be abandoned, as alternative between these two suborders. But the shape of the pelvis itself is sharply diagnostic in this regard, for while it is nearly straight transversely, or bowed forward only very slightly, in all the Rajoidea for which its shape is known[2] and has a projection (longer or shorter) directed forward from each of its outer corners, its transverse element is bowed strongly forward, and it has no prepelvic projections at the outer corners in all the myliobatoid families where it has been studied, but has a prepelvic process in the mid-line in some of them.[3]

The presence or absence of vestiges of the embryonic gill filaments on the anterior wall of the spiracle, after birth, seems equally diagnostic, as between the suborders Rajoidea and Myliobatoidea, for these are present in various species of *Raja*, in *Breviraja*, in *Cruriraja*, in *Springeria* and in *Pseudoraja*, whereas no trace of them is to be seen in any of the myliobatoids where we have sought them, which include representatives of *Dasyatis*, *Taeniura*, *Gymnura*, *Urolophus*, *Myliobatis*, *Aetobatus*, *Rhinoptera* and *Mobula*.

The taxonomic significance of this character was forecast, in fact, more than a century ago, by Johannes Mueller's (Arch. Anat. Physiol. Jahrg. 1841, p. 274) discovery that these vestigial gill folds are present after birth in skates and in torpedos, as they are in many sharks, but not in *Myliobatis*, in *Dasyatis* (referred to by him as *Trygon*), or in *Taeniura*. But while the contrast in this respect, between skates and sting rays, has been mentioned repeatedly since Mueller's day, we can not find that any of our predecessors have taken account of it in defining the two subfamilies in question.

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[1] For illustration of the pelvics in *Sympterygia*, see Garman, 1913, Pl. 27, Fig. 1.

[2] This includes representatives of the genera *Raja*, *Breviraja* and *Cruriraja* (Family Rajidae), and of *Springeria* representing the Anacanthobatidae. The shape of the pelvis is not known for the somewhat problematical family Arhynchobatidae.

[3] See Garman (1913, Pls. 53, 54) for illustrations of the pelvis in Dasyatidae, Potamotrygonidae, Gymnuridae, Urolophidae, Myliobatidae and Mobulidae.

Pseudoraja, in short, falls clearly among the Rajoidea. But its lack of dorsal fins with its well developed caudal fin forbid its reference either to the Rajidae or to the somewhat problematical family Arhynchobatidae, while the nature of its pelvic fins, the large size of its caudal, and its well developed dermal armature set it apart, equally sharply, from all known members of the Anacanthobatidae. Hence the necessity for a new family, lest it be left a taxonomic orphan.

Genus PSEUDORAJA Gen. Nov.

Generic characters. Pseudorajidae with shape of disc, and of tail relative to disc, as in skates of the family Rajidae; pelvic fins very large, wing-like, with anterior outline directed outward, about transverse to main axis of disc; front of cranium with a rostral projection, longer or shorter; a deep pit on ventral surface of head on either side, close posterior to nostril but entirely separate from latter. Other characters those of family Pseudorajidae. Type species *Pseudoraja fischeri* Bigelow and Schroeder.

PSEUDORAJA FISCHERI,[1] Sp. Nov.

Figures 1, 2

Type. Female, 479 mm. long, southern part of Gulf of Mexico, near Campeche Bank, Lat. 22°42′N, Long. 86°41′W, 225 fathoms, OREGON Sta. 726; bottom temp. 47.7°F; U. S. Nat. Mus. No. 163368.

Study material. Also female 428 mm.; female 262 mm., and juvenile male 262 mm. from same station.

Description. Proportional dimensions, in per cent of total length, of female 479 mm. long (type) and female, 428 mm.

Disc: Extreme breadth, 48.6, 50.3; length 39.5, 40.0.

Snout length in front of:[2] orbits 9.2, 8.4; in front of mouth 12.3, 12.1.

Orbits: Horizontal diameter 4.4, 4.7; distance between 3.0, 3.0.

Spiracles: length 2.3, 2.2; distance between 6.0, 6.1.

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[1] Named in recognition of E. N. Fischer's skillful portrayals of elasmobranchs.

[2] From base of rostral filament.

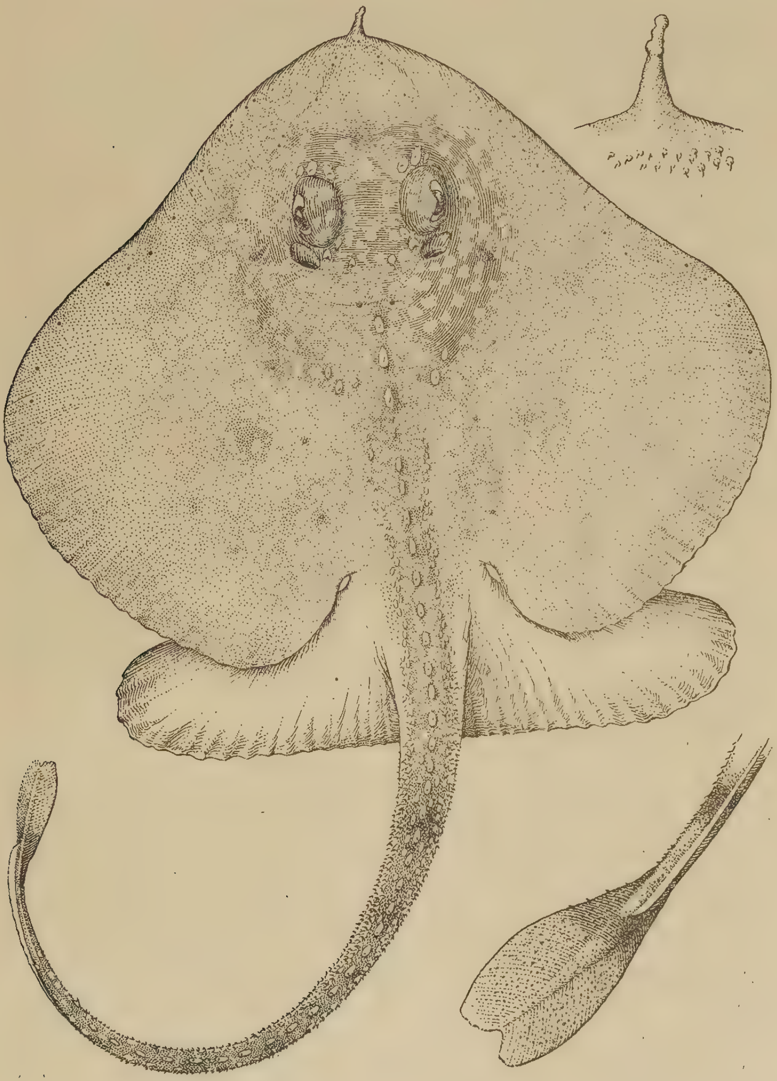

Fig. 1. *Pseudoraja fischeri,* type specimen 479 mm. long. Rostral filament and side view of caudal fin to larger scale. U. S. Nat. Mus. No. 163368.

Mouth: breadth 4.7, 4.6.

Nostrils: distance between inner edges 6.4, 6.3.

Gill openings: lengths, 1st 1.0, 1.1; 3rd 1.2, 1.2; 5th 0.7, 0.7; distance between inner ends, 1st 11.2, 11.8; 5th 6.9, 7.0.

Caudal fin: length of base, upper 7.7, 8.2; lower 6.9, 7.3.

Distance: from tip of snout to center of cloaca 39.5, 38.5; from center of cloaca to tip of tail 60.5, 61.5.

Pelvics: anterior margin 17.7, 17.7.

Teeth: $\frac{28}{26}$ in type; $\frac{30}{26}$ in female of 428 mm.; $\frac{28}{28}$ in male of 262 mm.

Disc, from base of rostral filament, about 1.2 times as wide as long, so broadly rounded in front that its anterior contour is not susceptible to angular measurement; the rostral filament about ⅓ as long as orbit, soft, narrow triangular, tapering to very slender but blunted tip. Anterior margins of pectorals weakly concave abreast of eyes and spiracles, convex thence rearward; outer corners broadly rounded; posterior margins moderately convex; posterior corners rather abruptly rounded; inner margins weakly convex, to axils. Tail slender, its dorsal surface nearly flat, but its sides and lower surface rather broadly arcuate in cross section; its breadth at axils of pelvics about 80 per cent as great as length of orbit, its length, from center of cloaca to tip, about 1.5 times as great as distance from center of cloaca to base of rostral filament; the lateral caudal folds confined to about posterior ⅓ of tail and extending a little beyond origin of caudal fin, very narrow along their anterior part, but widening rearward until

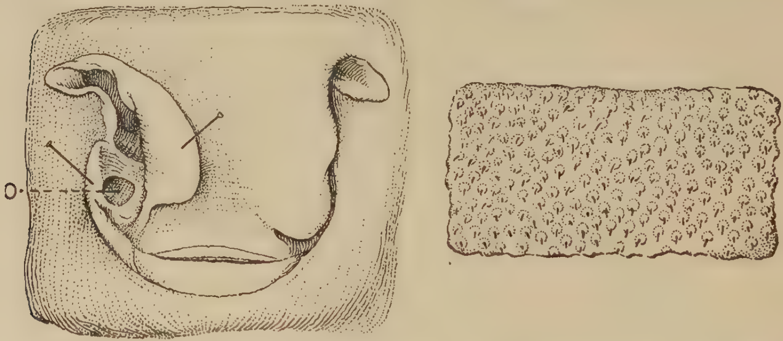

Fig. 2. *Pseudoraja fischeri.* Left, ventral view of oronasal region with right hand nasal flap rolled back to show nostril and oronasal pit (0). x about 1. Right, skin from central part of pectoral, to show arrangement of prickles. x about 3 1/2.

nearing the level of the caudal fin. The breadth of the folds is about ½ as great as the height of the caudal above its axis, or about ⅔ as great as the length of the first gill openings.

Entire upper surface of disc including skin above eyes, and of tail close set with minute, sharp pointed prickles curving rearward, except close along extreme posterior edge of pectorals; also two large and one small thorn around anterior contour of orbit, the small one the outermost; a group of two large and one smaller thorn close behind each orbit, with the largest member of the group the outermost; two thorns on each shoulder, with a median line of three from nuchal region to pectoral girdle; these are followed, after a short gap, by a row of about 32 along mid-line of disc and of anterior ⅔ of length of tail, the first five to pelvic girdle small, the next 17 or 18 large and conspicuous, with strongly striate bases, those farther rearward, along tail, progressively smaller; and the posterior ¼ of tail without large thorns, recalling conditions in *Raja senta.* Either side of mid-dorsal belt of disc and upper side of tail with 3–4 irregular rows of closely crowded thornlets; no thorns large or small (apart from the prickles) anywhere on pectorals. Caudal fin generally prickly above caudal axis, but with only a few scattered prickles below axis. Upper surface of pelvics wholly naked. Lower surface of disc and of pelvics naked, also of anterior part of tail rearward to abreast of rear corners of pelvics, but densely prickly thence rearward to caudal fin. The dermal armature of small specimens essentially similar, except the mid-dorsal thorns fewer (about 26 in 2 specimens of 262 mm.).

Snout (from base of terminal filament) to front of orbits about 2.9 times as long as distance between orbits, its length in front of mouth about 1.9 times as great as distance between inner edges of exposed nostrils. Orbit about 1.5 times as long as distance between orbits and about 2.1 times as long as spiracle. Upper eyelid bowed downward, and eye with a rounded black velum with crenate margin above pupil, as in skates of the genera *Raja* and *Breviraja.*

Outer lip of spiracle smooth; vestigial gill-ridges on anterior surface of spiracle about 12 in number, rounded, their edges completely fringed with minute lobelets. Nasal curtains smooth edged; those of the two sides of head actually separated by a space about ½ as wide as distance between exposed nostrils, but seemingly interconnected there by a weakly outlined fold of skin. Outer (posterior) margin of nostril smooth, slightly expanded in scoop-like form; the exposed nasal aperture noticeably small.

An interesting feature of this new skate is that if the nasal curtain, on either side, be rolled inward, and the skin between nostril and corner of mouth be spread outward, a deep pit is exposed, close behind the nostril, but its entrance separated from the latter by a bar of stiff tissue. The pit is directed forward-upward, and it extends so far that a probe inserted into it can be felt clearly from the dorsal side of the head, through the overlying skin. And it is so voluminous on the two larger specimens as to allow the entrance of an ordinary match stick, or of a slender lead pencil. The presence of this pit was wholly unexpected, for nothing comparable to it is to be seen, either in *Raja*, in *Dasyatis*, or for that matter in any of the other batoids that we have examined in this respect, and these include representatives of all known families, both of Rajoidea and of Myliobatoidea, excepting only the Arhynchobatidae.

Mouth nearly straight transversely in females and in juvenile males, its contour not known for adult males. Teeth $\frac{28\,(\text{type})\text{–}30}{26\,(\text{type})\text{–}28}$; those of females and of juvenile males low, rounded, in quincunx mosaic; those of mature males not seen; the tooth bands attached rather loosely to the jaws.

First gill openings about $\frac{1}{6}$ as long as distance between exposed nostrils; third gills a little longer than first; fifth gills about 7/10. Distance between inner ends of first gills about 1.8 times as long as between inner edges of exposed nostrils and about 1.7 times between inner ends of fifth gills.

No dorsal fins. Caudal fin a little longer than distance between exposed nostrils, its height above caudal axis about $\frac{1}{4}$ as great as its length, its depth below axis about $\frac{4}{5}$ as great as its height above latter; upper and lower caudal origins about even. Upper margin continuously rounded; lower margin less strongly so; tip broadly rounded, notched abreast of tip of axis in type specimen, but merely ragged there on slightly smaller specimen (428 mm.) and continuously rounded terminally in small specimens (262 mm.), evidence that its terminal contour on the type has resulted from mutilation.

Pelvic fins more widely spreading than in most other rajoids, and of very diagnostic shape, the anterior outline directed nearly transversely to the main axis of disc and tail, and so long that the tips of the pelvics reach outward considerably beyond the margins of the overlying portion of the pectorals. Anterior margin nearly straight; outer corners broadly rounded; outer posterior (distal) margin straight, or very weakly convex if spread widely; only very weakly scalloped to conform to positions of tips of radial cartilages; the rear corner abruptly rounded. The inner margin is so short that the pelvics of the two sides appear to be separated only by a shallow notch. But the condition of the clasper described below shows that this is not evidence of a partial fusion of the inner edges of the pelvics with the sides of the tail, but only that these edges are relatively shorter than they are in the skates of the genera *Raja* and *Breviraja*. The anterior margin of the fin soft and fleshy; the first radial cartilage noticeably stout, especially toward its base; the other radialia slender and flexible.

Point of separation of clasper from inner margin of pectoral, in juvenile male, about even with the axil of the fin; tip of clasper already reaching a little beyond rear corner of pelvic. Claspers of mature male not seen.

It is interesting, in this connection, that the claspers of juveniles of *Springeria* originate considerably in advance of the apparent axils of the fins, evidence of partial fusion of the inner margins of the latter with the sides of the tail (Bigelow and Schroeder, 1951, Fig. 1).

Front of cranium with a low, blunt tipped rostral projection, reaching forward a little beyond level of fronts of nasal capsules; tips of anterior rays of pectorals reaching nearly to tip of snout. Pelvis with transverse element nearly straight, each outer corner with a short prepelvic projection.

Color. Upper surface ashy gray, deepening rearward to sooty gray along posterior 4/5 of tail; disc rearward from orbits with many small vaguely outlined pale spots, most conspicuous on head, and along mid-belt thence rearward, less so outward over pectorals; outer parts of pectorals unspotted. The large thorns white basally, their tips gray. Anterior part of disc also with a rather conspicuous pattern of black dots marking the mucous pores as follows: a) an irregular row along outer margin of each pectoral from a little behind tip of snout to about abreast of axis of greatest breadth; b) a row of 7–8 on each side, diverging from tip of snout to a little in front of level of front of orbits; c) a row of four, extending in anterior-posterior direction close in front of each orbit; d) a larger black spot, marking a cluster of three or four pores a little outward and rearward from the posterior edge of each orbit; e) a similar black spot (3 or 4 pores) either side of the mid-line in nuchal region, close in front of the first large mid-dorsal thorn; f) one black dot (1 pore) on inner part of each pectoral, in shoulder region; a second in line of orbit a little rearward from shoulder region; and a third about midway thence toward axil of pectoral. Tail irregularly pale spotted along anterior ½, with a few scattered pale spots thence rearward to caudal fin; also with a vaguely outlined dark cross-bar a little posterior to level of tips of pelvics, followed, after a short gap, by a second such bar. Upper surface of pelvics ashy gray, without pale spots.

Lower surface of disc ash gray with irregular sooty cloudings, these most conspicuous on abdominal region; the pectorals of a more brownish, the mid-belt of a more bluish cast. Lower surface of pelvics ashy gray, with bluish cast; lower surface of tail pale grayish white with irregular ashy-gray cloudings, and with the dark cross-bars of the upper surface encroaching downward across the sides rather conspicuously.

The pale spots on the disc are much less conspicuous, and less definitely outlined on small specimens than on large, but the dark cross-bars on the tail are more conspicuous.

Size. The larger specimens being female, and our only male a juvenile, their sizes give no clue to the dimensions to which this skate may grow.

Habits. Apparently confined to rather deep water.

Range. So far known only from the southern side of the Gulf of Mexico, at the locality listed above, page 4.

Family RAJIDAE

Raja fuliginea, Sp. Nov.

Figures 3, 4

Study material. Type specimen. A juvenile male, 306 mm. long, OREGON Sta. 534, northwestern part of Gulf of Mexico, Lat. 27°32′N, Long. 93°02′W; trawl haul at 400–450 fathoms, April 11, 1952; U. S. Nat. Mus., No. 163367.

Distinctive characters. This skate resembles *R. bathyphila* Holt and Byrne 1908 so closely in the general arrangement of thorns and prickles, in proportional dimensions in general, and especially in the very dark coloration of the lower surface of disc and tail that we took it for a specimen of *bathyphila* on our first cursory glance. But a closer examination showed that it differs from *bathyphila* in a considerably more obtuse anterior contour of its disc (Fig. 3A) and especially in the fact that the entire lower surface of the tail, apart from a very narrow median stripe, is densely prickly from base to tip (naked in *bathyphila*). The prickles, also, on the upper surface of disc and tail are coarser than on *bathyphila*, and there are no naked areas, while its pelvics are largely prickly on the upper surface (naked in *bathyphila*)

The only skate yet known from the northwestern Atlantic, or from the Gulf of Mexico, other than *R. bathyphila*, with which *fuliginea* shares a uniformly dark colored lower surface is *R. olseni*. But it differs from *olseni* in blunter snout and tail prickly below. It shares a tail prickly below with *R. mollis*. However, it is marked off from *mollis*, not only by its dark lower surface (*mollis* is pale yellowish or whitish below) but also by a much thornier tail and disc, by its considerably more convex anterior contour, also by its harder rostral cartilage. Since these divergences concern characters that are not generally subject to much individual variation among the members of its genus, a new specific name seems requisite for it. We suggest *fuliginea* because of the sooty chocolate hue of its lower surface.

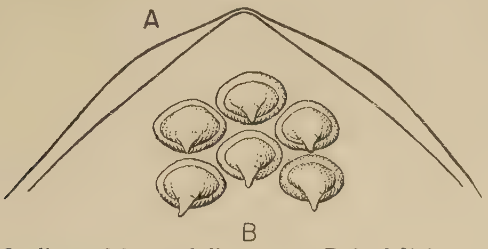

Fig. 3. A. Outlines of front of disc; outer, *Raja fuliginea*, type specimen, and inner, *Raja bathyphila* from southern slope of Georges Bank to show difference in shape. B. Upper teeth of *Raja fuliginea* from near center of mouth. x about 15.

R. fuliginea, like *bathyphila* and *olseni*, parallels *R. badia* Garman 1899, *R. trachura* Gilbert 1892, and *R. abyssicola* Gilbert 1895 of the Pacific coast of Central and North America in its uniformly dark lower surface. But it differs sharply from all three of these in various respects.

Description. Proportional dimensions, in per cent of total length. Juvenile male, 306 mm. long; OREGON Sta. 534, northwestern part of Gulf of Mexico, Lat. 27°32′N; Long. 93°02′W; 400–450 fathoms.

Disc: Extreme breadth 46.3; length 42.8.

Snout length in front of: orbits 9.8; mouth 12.1.

Orbits: horizontal diameter 3.9; distance between 3.6.

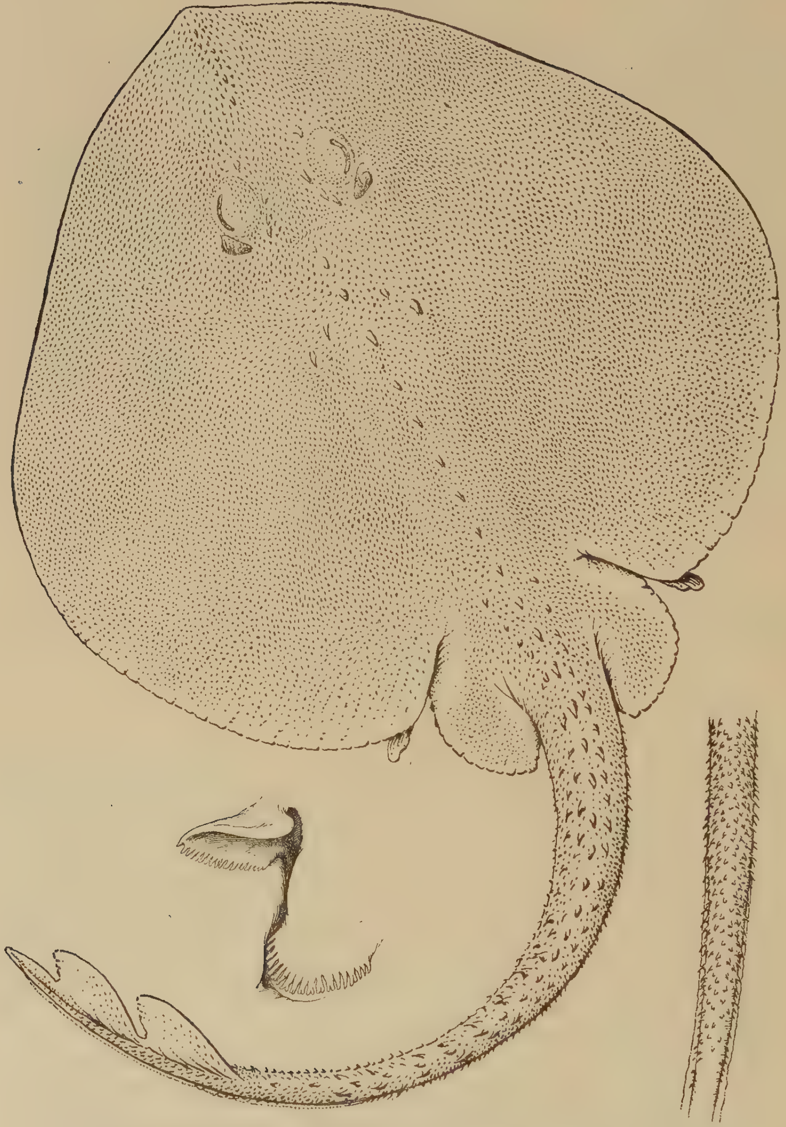

Fig. 4. *Raja fuliginea,* type specimen 306 mm. long, U. S. Nat. Mus. No. 163367, with right hand nostril and nasal curtain x about 3.4, and under side of tail in advance of first dorsal fin, x about 1.1.

Spiracles: length 2.3; distance between 6.7.

Mouth: breadth 5.9.

Nostrils: distance between inner ends 6.2.

Gill openings: lengths 1st 1.3; 3rd 1.3; 5th 1.0; distance between inner ends, 1st 12.9; 5th 7.5.

Distance: from tip of snout to center of cloaca 39.3; from center of cloaca to 1st dorsal 45.4; to tip of tail 60.7.

First dorsal fin: vertical height 2.9; length of base 5.9.

Second dorsal fin: vertical height 2.6; length of base 5.6.

Interspace between: 1st dorsal and 2nd dorsal 0.0.

Pelvics. anterior margin 14.4.

Teeth: $\frac{41}{42}$.

Disc about 1.1 times as broad as long, so broadly and continuously rounded in front that the anterior contour is not susceptible to angular measurement; the tip of the snout projecting slightly, and blunted. The pectoral margins only very slightly concave abreast of eyes and spiracles, and broadly and continuously rounded thence rearward, around to posterior corners, without definitely marked outer corners; posterior corners rather abrupt; inner margins nearly straight.

Axis of greatest breadth about ⅔ (66%) of distance rearward from tip of snout toward level of axils of pectorals.

Tail with very narrow lateral folds along posterior ⅖ (38–39%) of its free length posterior to axils of pelvics; its length from center of cloaca about 1.2 times as great to first dorsal and about 1.5 times as great to tip as from center of cloaca to tip of snout.

Upper surface of disc, also upper surface and sides of tail, densely set everywhere with rather coarse prickles curving rearward, or minute thornlets, a very narrow band close along posterior edges of pectorals being the only naked area.

Also a group of small recurved thorns along anterior part of rostral ridge; four larger thorns in a line around inner side of each orbit; one thorn in mid-line in nuchal region; six large thorns on scapular region, two of these on either side with two in mid-line in pattern shown in Figure 4; a line of six smaller thorns along mid-line of disc from scapular region nearly to level of axils of pectorals, followed, thence rearward, by 3–4 irregular rows along anterior ⅘ of tail, succeeded by two thorns in mid-line, to first dorsal fin. First and second dorsals, and caudal membrane sparsely prickly; anterior lobes of pelvics naked; posterior lobes rather densely prickly over inner and posterior portions.

Lower surface of disc naked throughout. Lower surface of tail densely set with prickles or thornlets similar to those of upper surface, except that a very narrow median stripe is naked, both along anterior ⅔ of tail, and, again, rearward from level of origin of first dorsal fin.

Snout in front of orbits about 2½ times as long as orbit; its length in front of mouth about twice as great as distance between exposed nostrils. Orbit about as long as distance between orbits and about 1.7 times as long as spiracle. Nasal curtain deeply fringed, with about 18 lobelets; expanded posterior (outer) margin of nostril fringed, also. Mouth nearly straight, the lower jaw arched forward only a very little centrally; its breadth about 1/5 (21%) as great as breadth of disc at level of mouth, and only about 6 per cent as great as distance from tip of snout to tip of tail. Teeth $\frac{41}{42}$, with low triangular cusp, blunted at tip, arranged in quincunx in juvenile male, probably also in female.

First pair of gill openings about 22 per cent as long as breadth of mouth; distance between inner ends of first gills about 2.1 times as long as between inner edges of exposed nostrils, and about 1.2 times between inner ends of fifth gills.

Dorsal fins about alike in shape and equal in size, their bases confluent, without intervening thorn or prickles. Caudal membrane, posterior to second dorsal, about ⅔ as long as base of second dorsal.

Pelvic fins deeply concave outwardly; outer margin strongly scalloped around the concavity with three marginal lobes on the one fin, four on the other; but with the positions of the radial cartilages only faintly indicated thence rearward; anterior lobe narrow, fleshy with rounded tip; posterior lobe strongly convex; rear corner abrupt; anterior margin of anterior lobe about 90 per cent as long as distance from its point of origin to rear corner of posterior lobe; rear corners extending back from about ¼ of distance from level of axils of pectorals toward first dorsal fin.

Firm rostral cartilage detectable by touch as reaching very nearly to extreme tip of snout; tips of anterior rays of pectorals falling a little short of level of tip of rostral cartilage.

Color. Upper surface of disc, tail and pectorals uniform dark ashy gray, darkest on anterior lobes of pelvics, but without definite dark markings anywhere. Lower surface of disc sooty chocolate to nearly black, and noticeably darker than upper surface on head and around outer belts of pectorals. A sub-triangular area in region of cloaca reaching forward about to pelvic girdle, and vaguely outlined, irregularly interrupted areas on the inner parts of the pectorals rearward from the gill region are of a somewhat paler sooty chocolate hue, perhaps partly as a result of rough treatment in the trawl. Lower surfaces of pelvics dark sooty, except pale on tips of anterior lobe; sides and lower surface of tail of a very dark ashy-gray, except somewhat paler along a narrow median stripe.

Size: The type (and only known) specimen being a juvenile male, it gives no clue to the size to which this skate may grow.

Habits and range. The depth of capture (400–450 fathoms), added to the dark color of its lower surface, marks *fuliginea* as a deep water species. Present indications are that the upper boundary to its usual range lies not far from 400 fathoms, else specimens of a skate made so conspicuous by its dark lower surface would almost certainly have been noticed among the catches of the many trawl hauls that have been made in the Gulf at lesser depths. Nothing more than this is known of its habits.

The locality of capture lies in the northwestern part of the Gulf, some 100 miles off Galveston. It is an interesting question for the future whether *fuliginea* is restricted to the Gulf, or whether it has simply been overlooked in the open Atlantic.

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Spectrophotometric Determination of Uric Acid and Some Redeterminations of Its Solubility

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The present study was initiated in order to develop a rapid and accurate method for the determination of uric acid in fresh, brackish, and sea water. It was found that the spectrophotometric determination of uric acid based upon its reaction with arsenophosphotungstic acid reagent in the presence of cyanide ion meets this objective. The absorbancy of the blue complex was measured at 890 mμ. Slight variations from Beer's law were generally found. The results show the effects of pH, reaction time, concentration of reagents, and temperature upon color development and precipitate formation. Disodium dihydrogen ethylenediamine tetraacetate (Versene) was used as a buffering and complexing agent. The results are significant in that they give the absorption spectrum of the blue complex and the effects of variables upon its absorbancy. Studies were made with the method to determine the stability of reagents and standard solutions and to determine the rate of bacterial decomposition of uric acid. Measurements of the solubility of uric acid are reported.

THE various methods for the determination of uric acid were studied critically by Hutchinson (*12*), who recommended preliminary separation of uric acid and its determination with arsenophosphotungstic acid or lithium arsenotungstate reagent.

The method for the determination of uric acid based upon its reaction with arsenophosphotungstic acid in the presence of cyanide ion to give a blue color was developed by Benedict and coworkers (*1–3*). The use of cyanide ion to increase the sensitivity of the method was first reported by Benedict and Hitchcock (*4*) in the case of phosphotungstic acid reagent. It was later shown to have the same effect with arsenotungstic acid reagent (*17*) and with arsenophosphotungstic acid reagent (*1*).

While there are no references to the structure of the blue-colored substance, it is probably related to tungsten blue or similar compounds. Sidgwick (*19*) ascribes the blue color formed on gentle reduction of tungstates to products containing tungsten-

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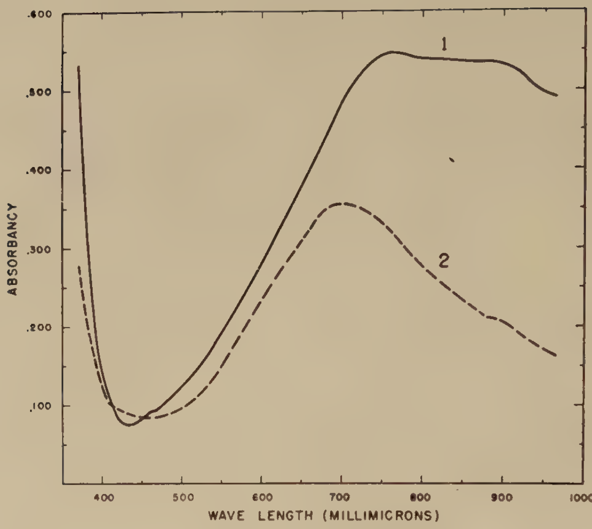

Figure 1. Absorption Spectra

1. **Absorption spectrum before 1 hour; 100γ uric acid per 50 ml.**
2. **Absorption spectrum at 24 hours; 40γ uric acid per 50 ml.**

(V) and (VI). Sidgwick also refers to a complex cyanide of tungsten(V) which cannot be further oxidized by strong oxidants. The stabilization of tungsten(V) by formation of a complex cyanide would shift the redox potential in the direction to increase the relative strength of tungsten(VI) as an oxidant toward uric acid. The resultant shift in the equilibrium would favor the formation of tungsten blue or related colored compounds.

While the method of Benedict and coworkers gives reliable results when close attention is given to a prescribed procedure, slight deviations from the procedure may cause significant errors. In modifying this method for the determination of uric acid in natural waters, studies were made of the effects of pH, reaction time, concentration of reagents, and temperature upon color development and precipitate formation. Disodium dihydrogen ethylenediamine tetraacetate (Versene) was used to control the pH of the reaction mixture and to complex alkaline earth ions in the natural water samples.

METHOD

Apparatus. Absorbancy measurements were made with a Beckman DU spectrophotometer and pH measurements with a Beckman Model G pH meter. A Model N Leeds and Northrup Electrochemograph was used to record the polarographic data.

Chemicals. Except where otherwise specified, inorganic chemicals are C.P. or reagent grade, while organic chemicals are Eastman White Label grade.

Disodium dihydrogen ethylenediamine tetraacetate dihydrate (Versene), Hach Chemical Co.

Sodium tungstate dihydrate, C.P. (Folin)

Uric Acid, C.P.

Reagent Solutions. Sodium cyanide, 10% solution.

Disodium dihydrogen ethylenediamine tetraacetate dihydrate (Versene), 4% solution.

Arsenophosphotungstic Acid Solution (Color Reagent). The solution was prepared according to the method of Benedict and

Franke (*3*). One hundred grams of sodium tungstate dihydrate were dissolved in 600 ml. of distilled water. Fifty grams of arsenic pentoxide, 25 ml. of 85% phosphoric acid, and 20 ml. of concentrated hydrochloric acid were added to the solution. After the solution had been brought to a boil, 20 ml. of bromine water were added and the boiling was continued for 2 hours. After cooling, the solution was diluted to 600 ml. (in the original procedure described by Benedict and Franke the solution was diluted to 1 liter). The pH of the clear yellow reagent was 1.48 and it was stable for a period exceeding 2 months. According to Benedict and Franke the solution should be practically colorless. In the Folin procedure using phosphotungstic acid reagent, the yellow color is attributed to phospho-24-molybdic acid and smaller blanks can be obtained by removing molybdenum (*7*).

Uric Acid Standard Solutions. The uric acid primary standard

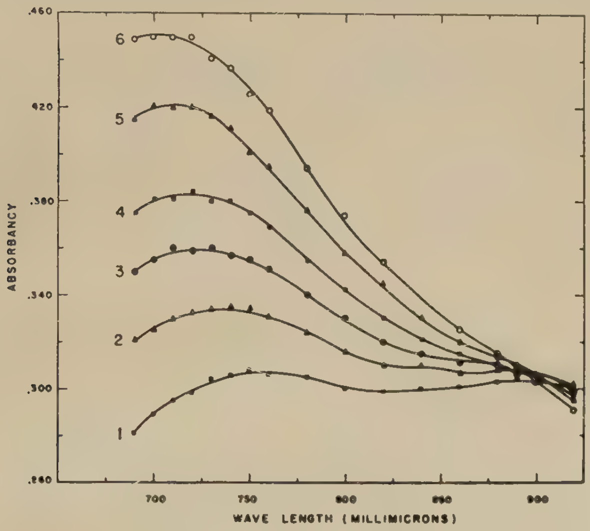

Figure 2. Effect of Time on Absorption Spectrum

	Minutes Elapsed after Addition of Color Reagent	
Curve No.	920 mμ	690 mμ
1	36	47
2	49	60
3	61	71
4	72	82
5	95	108
6	132	143

Table I. Effect of pH on Color Development and Precipitate Formation[a]

(Reagent concentrations varied)

Color Reagent, Ml.	10% NaCN, Ml.	Color of Soln.	pH	Minutes before Pptn.	Absorbancy at 890 mμ
2.50	1.00	Yellow	5.4	..	0.035
2.50	2.00	Bluish-green	6.3	..	0.130
2.50	4.00	Blue	8.1	..	0.310
2.50	6.00	Blue	8.7	30	...
2.50	8.00	Blue	9.1	10	...
0.50	4.00	Blue	9.0	50	...
1.00	4.00	Blue	8.9	50	...
1.50	4.00	Blue	8.6	50	...
2.00	4.00	Blue	8.4	50	...
2.50	4.00	Blue	8.1	..	0.310

[a] Conditions. 12 ml. of Versene and 5.00 ml. of dilute uric acid standard were added to flasks containing the volumes of reagents indicated. After diluting to 50.0 ml. and allowing to stand 50 minutes, pH and absorbancies were measured. The sodium cyanide solution was freshly prepared.

solution was prepared according to a modification of the method of Benedict and Hitchcock (*4*). Nine grams of sodium monohydrogen phosphate dodecahydrate, 1 gram of sodium dihydrogen phosphate monohydrate, and 0.2000 gram of uric acid were dissolved in 500 ml. of distilled water at 50° C. After cooling, the solution was diluted to 1 liter. By using sterile equipment, adding several milliliters of chloroform, and keeping the solution refrigerated, the primary standard was kept for 1 month without decomposition. The pH of the standard solution was 7.20. Although the original procedure calls for the addition of acetic acid to the primary standard solution, it was omitted in this work as it was found to lower the pH to 5.62, thereby causing the precipitation of uric acid.

A secondary standard solution was prepared immediately prior to use by diluting a 25-ml. aliquot of the primary standard solution to 500 ml. One milliliter of this solution contains 10γ of uric acid. It is important to use freshly prepared secondary standards as uric acid–utilizing bacteria may be present and their action in decomposing uric acid is rapid.

Procedure. An aliquot of the natural water sample, or standard solution, containing between 20 and 120γ of uric acid is transferred to a 50-ml. volumetric flask and diluted to 30.0 ml. Twelve milliliters of 4% Versene solution are added, 2.50 ml. of arsenophosphotungstic acid solution and 4.00 ml. of 10% sodium cyanide solution are introduced from burets, and the solution is mixed. (The usual precautions should be taken in handling and disposing of the poisonous solutions.) After standing the required length of time, the solution is made up to volume, mixed thoroughly, and the absorbancy measured in 1-cm. cells at 890 mμ against a reference cell containing distilled water.

A blank and a standard should be determined with each set of samples. It is recommended that a calibration curve be determined frequently and that the uric acid concentration be read directly from the curve.

The time required for the absorbancy to reach a maximum depends largely upon the age of the cyanide solution and this must be determined experimentally. If a turbidity develops in the solution prior to reading the absorbancy, it is necessary to change the ratio of the volume of the color reagent to the volume of the cyanide solution until optimum conditions are obtained. It was determined experimentally that the salt content of natural water samples has no effect upon color development.

DISCUSSION

Absorption Spectra. The absorption spectrum of the blue complex formed by the reaction of uric acid with arsenophosphotungstic acid reagent in the presence of cyanide ion changes with time. Curve 1 of Figure 1 shows the absorption spectrum of the blue complex early in its development. It has a high absorbancy between 430 and 960 mμ with a plateau between 730 and 900 mμ. When observed for longer periods of time the absorbancy at 890 mμ is practically constant, while absorbancies in the range 680 to 870 mμ continue to increase as illustrated in Figure 2. If the reaction is allowed to continue 24 hours, a maximum is found at 700 mμ as shown in curve 2 of Figure 1. Since the absorbancy at 890 mμ reaches a maximum in a comparatively short time, the absorbancy at this wave length is used to determine the concentration of uric acid in the reaction mixture. The absorption spectrum of the reagent blank shows the same characteristics as described above.

Effect of pH. By changing the amount and ratio of arsenophosphotungstic acid and sodium cyanide solutions it was possible to develop the color in reaction mixtures between pH 5.4 and 9.1. The results in Table I show that absorbancy increases with pH. The absorption spectrum of the light yellow solution

Table II. Effect of pH on Color Development and Precipitate Formation[a]

(Reagent concentrations constant)

pH	Absorbancy at 890 mμ
6.40	0.105
8.02	0.215
8.20	0.236
8.20	0.236
8.32	0.232
9.00	Ppt. formed

[a] Conditions. Small amounts of NaOH or hydrochloric acid were added to flasks containing 12.0 ml. of Versene and 5.00 ml. of dilute uric acid standard. After addition of 2.50 ml. of color reagent and 4.00 ml. sodium cyanide, the reaction mixtures were diluted to 50 ml. and allowed to stand for 25 minutes before pH and absorbancies were measured. The sodium cyanide solution was 1 month old.

Table III. Absorbancies at 890 mμ as a Function of Uric Acid Concentration and Reaction Time

Uric Acid, γ/50 Ml.	Reaction Time, Min.						
	34	36	41	46	51	56	61
0	0.031	0.032	0.034	0.036	0.038	0.039	0.039
20	0.091	0.092	0.095	0.097	0.098	0.097	...
40	0.171	0.172	0.174	0.176	0.175	0.173	...
60	0.258	0.258	0.261	0.261	0.260	...	...
80	0.355	0.355	0.354	0.353	0.349	...	...
100	0.445	0.445	0.445	0.442	0.441	...	...

at pH 5.4 has the same characteristics as the blue solution at pH 8.1, with the exception that the relative absorbancies below 550 mμ are much greater in the former case. The blue solution at pH 8.1 was perfectly clear and gave no Tyndall beam.

At pH 8.4 and above a white crystalline precipitate formed. It was soluble in strong base, precipitated from strong acid, and gave a characteristic test for tungstate ion. Since the formation of the precipitate limits the pH range for this method, further experiments were made to determine the effect of pH upon color development. Keeping the concentrations of the reagents constant, the pH was changed by adding varying amounts of hydrochloric acid and sodium hydroxide. The results of this study reported in Table II show conclusively that pH is the important factor in controlling color development and precipitate formation. The increase of sensitivity with pH may be attributed to the increase of cyanide ion concentration.

Reaction Time. The time required for the absorbancy to reach a maximum varies between 10 and 60 minutes, depending upon the conditions employed, and must be determined experimentally. The absorbancy is then constant for a period of 5 to 20 minutes before it begins to decrease. The time required for maximum color development depends to some extent upon the concentration of uric acid. As shown in Table III the absorbancy at 890 mμ reaches a maximum more rapidly with increasing concentration of uric acid. This may account for the observed deviations from Beer's law.

Forsham *et al.* (*8*) used sodium polyanethole sulfonate to stabilize the colored complex in a modification of the Kern-Stransky method (*14*) employing Folin reagent (*7*) and it is possible that it would be beneficial in this method.

Concentration of Reactants. The results in Table IV illustrate

Table IV. Effect of Concentration of Reactants on Color Development[a]

Volume during Color Development, Ml.	Absorbancy at 890 mμ
22	0.475
27	0.454
32	0.400
47	0.388

[a] Conditions. Varying amounts of distilled water were added to flasks containing 12.0 ml. of Versene and 4.00 ml. of dilute uric acid standard. Two milliliters of color reagent and 4.00 ml. of sodium cyanide were added and the color developed at the volumes indicated. After 45 minutes the solutions were diluted to 50.0 ml. and the absorbancies measured.

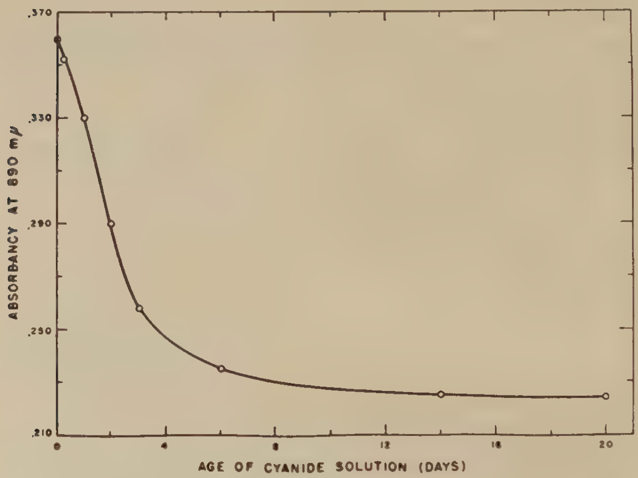

Figure 3. Effect of Age of Cyanide Solution

Absorbancies measured at 890 mμ; reaction time, 50 minutes; 50γ uric acid per 50 ml.

that absorbancy is proportional to the concentration of reactants during color development. Therefore, it is important to adjust the volume of solution prior to the addition of reagents. In the adopted procedure the sample, or standard, is adjusted to 30.0 ml. before the addition of reagents and the volume during color development is 48.5 ml.

Temperature. From 5° to 33° C. temperature had no effect on absorbancy while between 33° and 50° C. the absorbancy increased 9%.

Decomposition of Sodium Cyanide Solutions. Ricca and D'Amore (*18*) concluded that the decomposition of sodium cyanide solutions was caused by hydrolysis of cyanide ion to hydrocyanic acid, sodium formate, and ammonia. Benedict used urea to stabilize sodium cyanide solutions (*1*). Benedict and Behre (*2*) added 2 ml. of concentrated ammonium hydroxide to each liter of sodium cyanide solution and reported that it improved during the first 2 to 3 weeks after its preparation but that it should not be used after 6 to 7 weeks. Margolin and Buchteyev (*15*) studied the stability of sodium cyanide solution with reference to its use in the Benedict procedure and stressed the importance of constructing calibration curves at frequent inter-

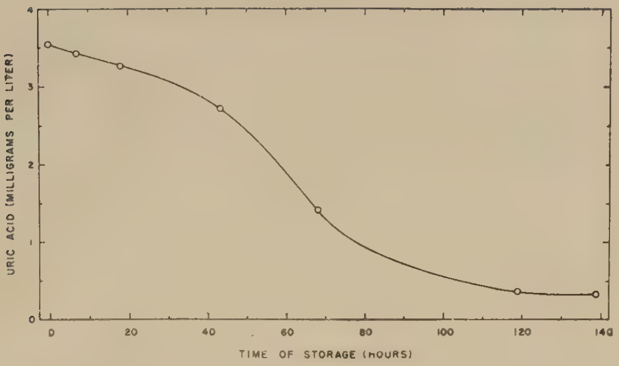

Figure 4. Decomposition of Uric Acid in a Brackish Water Sample

Sample stored at 3° C.

Table V. Solubility of Uric Acid at 30.2° C.

Redistilled Water, Ml.	Sea Water (Chlorinity 20.21 o/oo), Ml.	pH	Solubility, Mg./100 Ml.
100	0	5.21	5.07
80	20	5.68	11.3
60	40	5.94	18.1
40	60	6.10	24.2
20	80	6.20	28.4
0	100	6.29	34.6

vals. Brown (*5*) studied the stability of cyanide solutions using phosphotungstate color reagent. The results of the present investigation shown in Figure 3 give further evidence for the rapid decomposition of this reagent. To avoid the high initial rate of decomposition of freshly prepared sodium cyanide solutions, they were allowed to stand for 2 weeks before use. The solutions were discarded when their sensitivities became too low.

Destruction of Uric Acid by Bacteria. The method described in this paper was used to study the distribution and bacterial decomposition of uric acid in fresh, brackish, and sea water samples taken in the neighborhood of poultry farms. The bacterial decomposition of uric acid occurs under both aerobic and anaerobic conditions and can be brought about by a number of different organisms (*6*, *11*, *16*). According to Karlsson and Barker (*13*) *Clostridium acidi urici* decomposes uric acid anaerobically to give ammonia, acetic acid, and carbon dioxide while allantoin and urea, which are products of the aerobic decomposition of uric acid, are neither formed nor decomposed. The present studies indicate that uric acid–utilizing bacteria are ubiquitous and that the rate of bacterial decomposition of uric acid is rapid. The concentration of a uric acid solution contaminated with bacteria decreased from 1.4 to 0.7 mg. per liter within 6 hours at room temperature. The decomposition of uric acid in a brackish water sample taken from the neighborhood of a poultry farm and stored at 3° C. was measured. The data presented in Figure 4 show that decomposition was appreciable even at this temperature. Since destruction of uric acid by bacteria can be rapid, it is

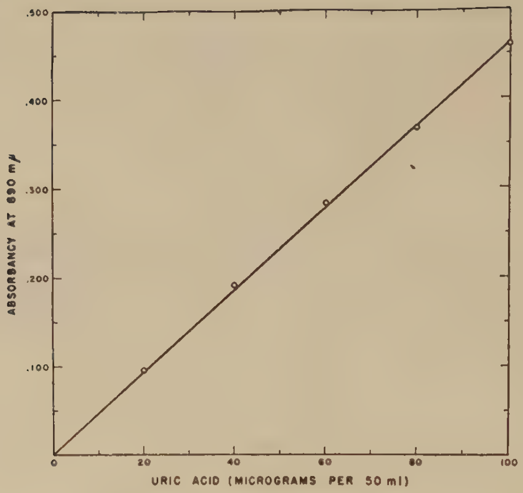

Figure 5. Calibration Curve

advisable to use sterilized equipment when feasible and to analyze the natural water samples as soon as possible after their collection.

Accuracy, Precision, and Sensitivity. The studies reported in this paper show the effects of pH, reaction time, concentration of reagents, and other variables on the accuracy, precision, and sensitivity of the method. In order to achieve accuracy it is necessary to construct calibration curves frequently. Even under optimum conditions absorbancy is seldom exactly proportional to concentration. Figure 5 is a calibration curve using the recommended procedure. Absorbancies were read 50 minutes after the addition of reagents and the reagent blank was 0.066 absorbancy units. In this case, using 2-week-old cyanide solution, Beer's law was closely followed. However, the age of cyanide solution has an effect on the shape of the calibration curve. With fresh cyanide solutions Beer's law was followed at concentrations greater than 40γ per 50 ml. but at lower concentrations the absorptivities were low. On the other hand, the absorptivities at these lower concentrations were high when cyanide solutions 3 weeks and older were used.

The precision of the method was determined by running blanks, standards, and samples in triplicate. The average deviations were less than 2%. It is possible to measure quantities as small as 2γ of uric acid in a total reaction volume of 50 ml. In a 20-ml. aliquot of a natural water sample the method is capable of measuring uric acid concentrations as low as 0.1γ per milliliter.

Interferences. Although the color reagent is not specific for uric acid in the presence of certain easily oxidizable substances, it appears to be highly selective in its action. For example, allantoin, barbituric acid, guanine, hydantoin, urea, and xanthine did not react with the color reagent at concentrations of 100γ per 50 ml. of reaction volume. Alloxan interfered at this concentration, 100γ giving an absorbancy which was equivalent to 20γ of uric acid.

A polarographic study was made to determine whether alloxan was a stable bacterial decomposition product of uric acid. Solutions of uric acid in natural waters were examined polarographi cally before, during, and after bacterial decomposition had taken place and no alloxan was detected. The apparent absence of interfering substances in natural waters makes it possible to use the method for the determination of uric acid directly. However, to be absolutely certain that interferences are not present it would be necessary to use the procedure on an aliquot of the sample after the uric acid was selectively oxidized by the enzyme uricase.

SOLUBILITY MEASUREMENTS

The solubility of uric acid in distilled water and in sea water of varying dilutions was determined. One hundred milliliters of the water and 0.5 gram of powdered uric acid were added to glass-stoppered Erlenmeyer flasks. The mixtures were placed on a mechanical shaker for 2 hours at 30.2° C. The pH of the unfiltered solutions was then determined. The samples were filtered through No. 42 Whatman filter paper and an aliquot was taken for the determination of uric acid. The results are shown in Table V. The solubility of uric acid in distilled water is 5.1 mg. per 100 ml. at 30.2° C. and its saturated solution has a pH of 5.21. The solubility of uric acid in sea water having a chlorinity of 20.21 grams per kilogram and an original pH of 8.29 is 35 mg. per 100 ml. at 30.2° C. and its saturated solution has a pH of 6.29. Intermediate values of uric acid solubility in sea water of varying dilutions are reported. The results are in general agreement with those of other investigators. Gudzent (*9*) gives a value for the solubility of uric acid of 6.49 mg. per 100 ml. of distilled water at 37° C. while His and Paul (*10*) report a value of 2.54 mg. per 100 ml. of distilled water at 18° C. In the same papers Gudzent reported an ionization constant for uric acid of 2.3×10^{-6} at 37° C. while His and Paul reported a value of 1.5×10^{-6} at 18° C. From these results it can be calculated that a substantial increase of solubility should occur at pH 5.6 and this relationship was found in the experiments reported. The large differences in the solubility of uric acid in natural water samples are therefore attributed to the pH of the solutions.

ACKNOWLEDGMENT

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GEOPHYSICAL INVESTIGATIONS IN THE EMERGED AND SUBMERGED ATLANTIC COASTAL PLAIN

PART VII. CONTINENTAL SHELF, CONTINENTAL SLOPE, AND CONTINENTAL RISE SOUTH OF NOVA SCOTIA

By C. B. Officer and M. Ewing

Abstract

The results of a series of refraction profiles made over the continental shelf south of Nova Scotia and extending down to the adjacent deep basin are reported. The resulting geologic and crustal sections show the manner in which the gradation from continent to ocean takes place. The Coastal plain sediments reach a maximum thickness of around 20,000 feet on the gently sloping area at the bottom of the continental slope and thin further seaward. The crystalline basement of metamorphic rocks and granites over Nova Scotia gradually thins under the continental margins and pinches out toward the ocean basins. It drops abruptly under the continental slope from 5000 feet to 20,000 feet. The Mohorovičić discontinuity is measured on a single profile at a depth of 52,000 feet under the continental rise.

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Introduction

During the summer of 1950 personnel from the Lamont Geological Observatory carried out an extensive deep-sea refraction program. As part of this program a series of profiles were made over the continental shelf from Georges Banks to Sable Island, extending the coverage of known structure of the Atlantic Coastal Plain sediments. In addition, the profile lines were carried out across the continental slope and over the adjacent deep ocean areas (Fig. 1). These data provided three cross sections of the sedimentary and crustal structure on the continental margins.

The geophysical techniques, equipment, and procedures used in these refraction operations have been described previously (Officer *et al.*, 1952, p. 777–783) and will not be repeated here. The methods of analysis were described by Ewing *et al.* (1939, p. 262–270). Continuous

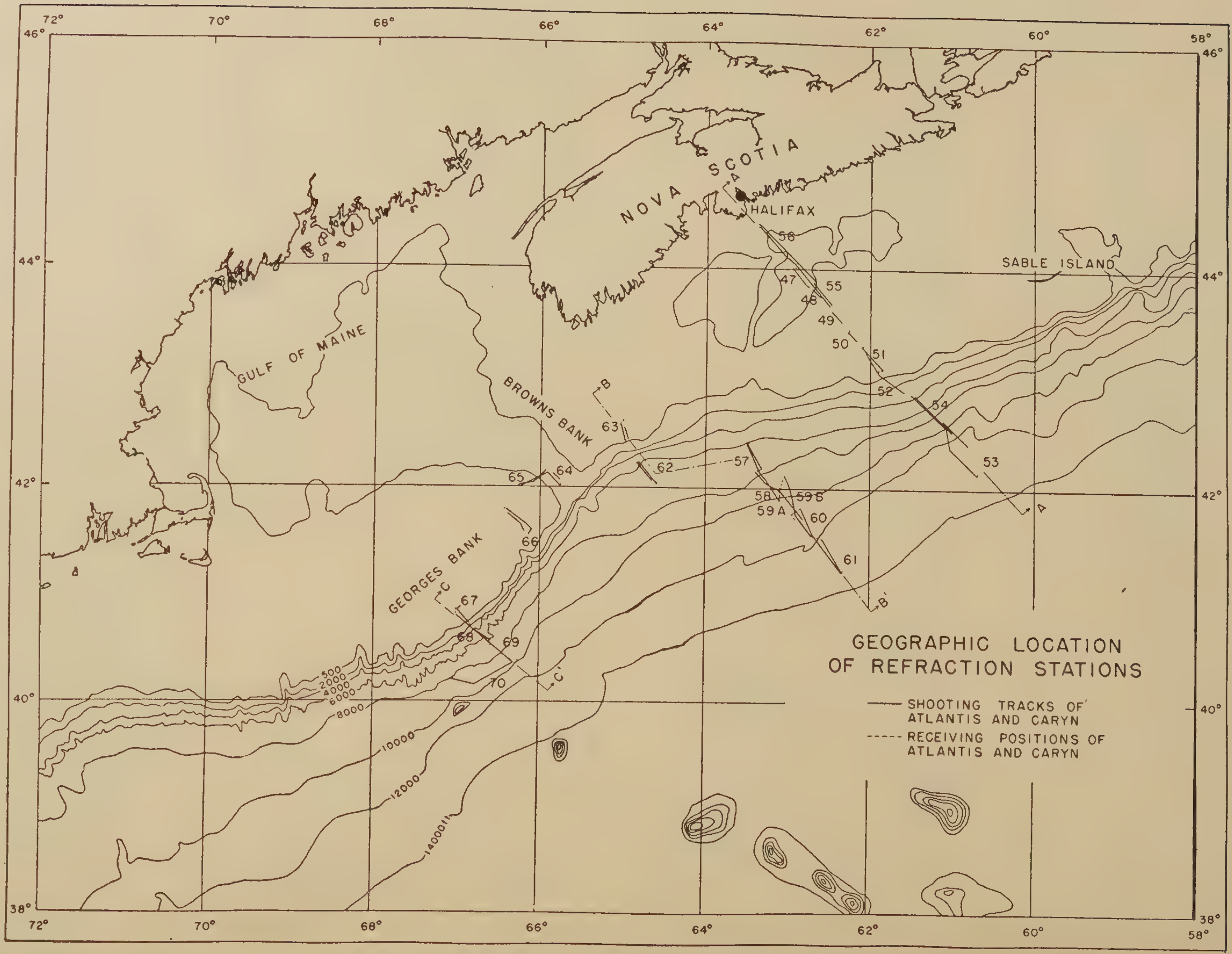
72°
70°
68°
66°
64°
62°
60°
58°
46°
44°
42°
40°
38°
NOVA SCOTIA
HALIFAX
SABLE ISLAND
GULF OF MAINE
BROWNS BANK
GEORGES BANK
A
A'
B
B'
C
C'
47
48
49
50
51
52
53
54
55
56
57
58
59 A
59 B
60
61
62
63
64
65
66
67
68
69
70
500
2000
4000
6000
8000
10000
12000
14000
GEOGRAPHIC LOCATION OF REFRACTION STATIONS
SHOOTING TRACKS OF ATLANTIS AND CARYN
RECEIVING POSITIONS OF ATLANTIS AND CARYN

FIGURE 1.—GEOGRAPHIC LOCATION OF REFRACTION PROFILES

echo-sounder records were taken along the shooting tracks of all the profiles.

Following the definition and usage of others the terms continental shelf, continental slope, and continental rise are defined topographically for this locality as follows. The continental shelf is the very gently sloping (less than ½°) area from landsend to a depth of water of about 500 feet (.15 km). The continental slope is the steeply sloping (2°–5°) area, from 500 to 7000 feet (.15–2.15 km). The continental rise is the gently sloping (about 1°) area from 7000 feet (2.15 km) out to the ocean basin. From Georges Bank west (Fig. 1) these three regions can be easily distinguished; but from Browns Bank to Sable Island the transition between the continental slope and continental rise is more gradual.

TABLE 1.—SEISMIC VELOCITIES

Profile	Unconsolidated sediment				Semiconsolidated Sediment		Consolidated Sediment		Basement (Granitic Layer)		Intermediate Layer		P_n	
	(1)		(2)											
	Ft/Sec	Km/Sec	Ft/Sec	Km/Sec	Ft/sec	Km/Sec	Ft/Sec	Km/Sec	Ft/Sec	Km/Sec	Ft/Sec	Km/Sec	Ft/Sec	Km/Sec
56	(5410)	(1.65)	....	....	.....	....	....	....	18770	5.72	....	....	....	....
47	5490	1.67	....	....	.....	....	....	....	15050*	4.59	....	....	....	....
55	(5410)	(1.65)	....	....	7430	2.26	....	....	19410	5.92	....	....	....	....
48	(5410)	(1.65)	....	....	9040*	2.76	....	....	16710*	5.10	....	....	....	....
49	5320	1.62	....	....	9080*	2.77	12330*	3.76	18500*	5.64	....	....	....	....
50	5720	1.74	....	....	9040*	2.76	11290*	3.44	18560*	5.66	....	....	....	....
51	5520	1.68	....	....	8140	2.48	12840	3.91	18360*	5.60	....	....	....	....
52	5410	1.65	....	....	9130*	2.78	....	....	17670*	5.39	....	....	....	....
63	5510	1.68	6130	1.87	8520	2.60	....	....	17650	5.38	....	....	....	....
64	(5580)	(1.70)	....	....	9210*	2.81	....	....	16050	4.89	....	....	....	....
65	5570	1.70	....	....	8770	2.67	....	....	15280	4.66	....	....	....	....
66	5690	1.74	....	....	8570	2.61	....	....	16720	5.10	....	....	....	....
67	6030	1.84	....	....	8520	2.60	....	....	16460	5.02	....	....	....	....
54	5910	1.80	....	....	9570	2.92	....	....	16840	5.13	....	....	....	....
53	5770	1.76	....	....	.....	....	....	....	14830	4.52	23190	7.07	....	....
62	(5600)	(1.71)	....	....	(9000)	(2.74)	....	....	16470*	5.02	....	....	....	....
57	5620	1.71	....	....	9220	2.81	....	....	13200	4.02	....	....	....	....
58	5920	1.81	6880*	2.10	9090*	2.77	....	....	13680	4.17	....	....	....	....
59	5690	1.74	6500	1.98	.....	....	....	....	14720	4.49	....	....	....	....
60	(5750)	(1.75)	6400	1.95	.....	....	....	....	(16000)	(4.88)	22680	6.91	....	....
61	(5750)	(1.75)	6350	1.94	.....	....	....	....	18170	5.54	23690	7.22	....	....
68	5580	1.70	6370*	1.94	(9650)	(2.94)	....	....	17460	5.32	....	...	....	....
..	....	....	....	....	.....	....	....	....	16760	5.11	....	....	....	....
69	5720	1.74	6880	2.10	10770	3.28	....	....	16400	5.00	22600	6.89	....	....
70	5500	1.68	(6880)	(2.10)	(10770)	(3.28)	....	....	15680*	4.78	21640*	6.60	27810*	8.48

* Unreversed velocities.

( ) Assumed velocities.

TRAVEL-TIME DATA AND GEOPHYSICAL RESULTS

General Discussion

This section is a discussion of the travel-time data from each seismic refraction profile. Its purpose is to indicate the degree of accuracy or uncertainty with which the refraction horizons were determined. In addition there is a discussion of the approximations that had to be taken in the final calculations on some of the less complete profiles and the justification for the particular approximations used. This section should be read in conjunction with the travel-time graphs of Plate I and Tables 1 and 2.

Continental Shelf Profiles

This group consists of profiles 47, 48, 49, 50, 51, 52, 55, 56, 63, 64, 65, 66, and 67. In general

TABLE 2.—THICKNESSES AND DEPTHS OF REFRACTION LAYERS

Profile	Thicknesses										Depths					
	Unconsolidated Sediment				Semiconsolidated Sediment		Consolidated Sediment		Water		Basement (Granitic Layer)		Intermediate Layer		Mohorovičić Discontinuity	
	(1)		(2)													
	Ft	Km	Ft	Km	Ft	Km	Ft	Km	Ft	Km	Ft	Km	Ft	Km	Ft	Km
56 N	50	.02	....	......	....	....	....	......	160	.05	210	.06	.....	.....	.....	.....
56 S	(1100)	(.34)	....	......	5010	1.53	....	......	700	.21	7020	2.14	.....	.....	.....	.....
47	570	.18	....	......	....	....	....	......	790	.24	1370	.42	.....	.....	.....	.....
55 N	480	.15	....	......	4250	1.30	....	......	710	.22	5440	1.66	.....	.....	.....	.....
55 S	550	.17	....	......	4090	1.25	....	......	290	.09	4930	1.50	.....	.....	.....	.....
48	1190	.36	....	......	1710	.52	....	......	600	.18	3500	1.07	.....	.....	.....	.....
49	1500	.46	....	......	2420	.74	6120	1.87	240	.08	10280	3.13	.....	.....	.....	.....
50	2120	.65	....	......	1650	.50	5230	1.60	300	.09	9300	2.84	.....	.....	.....	.....
51 N	1250	.38	....	......	3170	.97	9530	2.91	330	.10	14280	4.35	.....	.....	.....	.....
51 S	2340	.71	....	......	3280	1.00	(9530)	(2.91)	330	.10	15480	5.08	.....	.....	.....	.....
52	2660	.81	....	......	6100	1.86	....	......	260	.08	9020	2.75	.....	.....	.....	.....
63 N	1600	.49	140	.04	5050	1.54	....	......	350	.11	7130	2.18	.....	.....	.....	.....
63 S	1140	.35	880	.27	4530	1.38	....	......	400	.12	6960	2.12	.....	.....	.....	.....
64 N	(1710)	(.52)	....	......	3300	1.01	....	......	800	.24	5810	1.77	.....	.....	.....	.....
64 S	1710	.52	....	......	3060	.93	....	......	840	.26	5600	1.71	.....	.....	.....	.....
65 N	1680	.51	....	......	5610	1.71	....	......	490	.15	7770	2.37	.....	.....	.....	.....
65 S	1700	.52	....	......	4850	1.48	....	......	290	.09	6840	2.08	.....	.....	.....	.....
66 N	1160	.35	....	......	4630	1.41	....	......	250	.08	6050	1.84	.....	.....	.....	.....
66 S	1490	.46	....	......	4950	1.51	....	......	320	.10	6770	2.06	.....	.....	.....	.....
67 N	1340	.41	....	......	3870	1.18	....	......	200	.06	5410	1.65	.....	.....	.....	.....
67 S	1580	.48	....	......	3390	1.03	....	......	670	.20	5630	1.72	.....	.....	.....	.....
54 N	6480	1.97	....	......	9720	2.96	....	......	3820	1.16	20000	6.10	.....	.....	.....	.....
54 S	6440	1.96	....	......	....	....	....	......	11500	3.51	17900	5.45	.....	.....	.....	.....
53 N	5670	1.73	....	......	....	....	....	......	11500	3.51	17200	5.25	36800	11.20	.....	.....
53 S	4140	1.26	....	......	....	....	....	......	13030	3.97	17200	5.25	41800	12.75	.....	.....
62	(3500)	(1.07)	....	......	7380	2.25	....	......	6920	2.11	17800	5.40	.....	.....	.....	.....
57 N	3080	.94	....	......	7290	2.22	....	......	5950	1.81	16300	5.00	.....	.....	.....	.....
57 S	4050	1.23	....	......	3270	1.00	....	......	7910	2.41	15200	4.65	.....	.....	.....	.....

58 N	5290	1.61	....	......	1150	.35	....	......	7810	2.38	14200	4.35	.....	.....	.....	.....
58 S	1210	.37	7130	2.17	....	....	....	......	9660	2.94	18000	5.50	.....	.....	.....	.....
59 N	1850	.57	7330	2.23	....	....	....	......	9650	2.94	18800	5.75	.....	.....	.....	.....
59 S	270	.08	6720	2.05	....	....	....	......	11720	3.57	18700	5.70	.....	.....	.....	.....
60 N	1160	.36	(8030)	(2.45)	....	....	....	......	10880	3.32	20100	6.10	28300	8.65	.....	.....
60 S	200	.06	(8030)	(2.45)	....	....	....	......	12160	3.71	20400	6.20	28700	8.75	.....	.....
61 N	1070	.33	8650	2.64	....	....	....	......	12130	3.70	21800	6.65	36300	11.05	.....	.....
61 S	400	.12	9420	2.87	....	....	....	......	14020	4.27	23800	7.25	33300	10.15	.....	.....
68 N	990	.30	(1000)	(.30)	1040	.32	....	......	1040	.32	4100	1.25	.....	.....	.....	.....
68 P	1390	.42	(1000)	(.30)	13440	4.10	....	......	3480	1.06	19300	5.90	.....	.....	.....	.....
68 S	1910	.58	(1000)	(.30)	5760	1.76	....	......	6520	1.99	15200	4.65	.....	.....	.....	.....
69 N	990	.30	2860	.87	6620	2.02	....	......	7130	2.17	17600	5.35	26000	7.95	.....	.....
69 S	1340	.41	3820	1.16	5560	1.70	....	......	9070	2.77	19800	6.05	30700	9.35	.....	.....
70	(1340)	(.41)	(3820)	(1.16)	5260	1.60	....	......	9100	2.77	19500	5.95	26400	8.05	52200	15.90

( ) Assumed thicknesses.

a rather simple structure is found. It consists of a low-velocity layer (5320–6030 ft/sec, 1.68–1.84 km/sec) termed the unconsolidated sediment, an intermediary-velocity layer (7430–9210 ft/sec, 2.26–2.81 km/sec) termed the semiconsolidated sediment, and a high-velocity layer (15050–19410 ft/sec, 4.59–5.92 km/sec) termed the basement. On profiles 49, 50, and 51 an additional layer of velocity 11,290–12,840 ft/sec (3.44–3.91 km/sec), termed the consolidated sediment was measured between the semiconsolidated sediment and the basement. On profile 63 a second unconsolidated sediment was measured. On none of these profiles was an additional horizon measured below the basement. Profiles 51, 55, 56, 63, 64, 65, 66, and 67 were received in both directions producing reversed profiles; profiles 47, 48, 49, 50, and 52 were unreversed.

Profile 56. This was the longest shelf profile shot; the reverse distance is 53 nautical miles. Shots extended nearly to the end on both halves. At the southern station the shots did not start close enough to measure the unconsolidated and semiconsolidated sediment, and at the northern end the unconsolidated sediment was probably too thin to be detected from the records. In the calculations a velocity of 5410 ft/sec was used for the unconsolidated sediment from the results of profiles 47 and 49, and, from profile 48, a thickness of 1100 feet for the unconsolidated sediment at the southern station, and a velocity of 9049 ft/sec for the semiconsolidated sediment. No break was detected in the basement refraction line on either half of the profile. If 45 nautical miles is taken as the minimum distance at which a break in this refraction line might be detected, a minimum depth of 45,000 feet is calculated for an underlying layer of 25,000 ft/sec.

Profile 47. This profile gave a good one-way determination of the basement from first arrivals and the unconsolidated sediment from second arrivals. The semiconsolidated sediment was not measured and was not included in the depth calculations. The unreversed velocity of 13 010 ft/sec for the basement was the lowest measured. The results of profiles 48, 55, and 56 show that there is a regional dip of the basement seaward from station 47 (Fig. 2). In the calculations this dip was included, giving a true velocity of 15,050 ft/sec, which is still considerably lower than that found on adjacent profiles. Whether this is a real variation in the basement velocity, a change in the overlying formations, or a change in the dip of the basement cannot be answered from this unreversed profile. That this lower horizon is the basement and not an intermediary zone, for instance the consolidated sediment of profiles farther seaward, is inferred from the results of the nearby profiles 48, 55, and 56.

Profile 55. This profile gave a good determination of the basement on both halves and of the semiconsolidated sediment at the southern station. For the northern station the line for the semiconsolidated sediment was drawn through the one measured arrival and the reverse point. The unconsolidated sediment arrivals could not be read from the records; a velocity of 5410 ft/sec from profiles 47 and 49 was used in the calculations.

Profiles 48. This profile gave a good determination of the basement from first arrivals and of the semiconsolidated sediment from second arrivals. The unconsolidated sediment arrivals could not be read from the records. A velocity of 5410 ft/sec for the unconsolidated sediment from profiles 47 and 49 was used in the calculations. The depths and velocities were computed assuming a zero slope of the basement and semiconsolidated sediment.

Profile 49. This profile measured the unconsolidated sediment from four second arrivals, the semiconsolidated sediment from one first arrival, and for the first time the consolidated sediment from three first arrivals. The basement was measured by only one arrival. A velocity of 18,500 ft/sec from profiles 50 and 51 was assumed for the calculation of the depth of the basement. Calculations were made with the assumption of zero slope of the basement, consolidated, and semiconsolidated sediment.

Profile 50. This profile is almost identical with profile 49 but has a slightly better determination of the basement. Calculations were made with the assumption of zero slope of the overlying layers.

Profile 51. This profile gave a good determination of the unconsolidated, semiconsolidated, and consolidated sediment on both halves. The basement was measured only at the northern station. In the calculations the basement was assumed to have zero slope.

Profile 52. This profile gave a good determination of the unconsolidated sediment from second arrivals and the semiconsolidated sediment and basement from first arrivals. The consolidated sediment was not measured and if present is very thin. In the calculations the basement and semi-consolidated sediment were assumed to be horizontal.

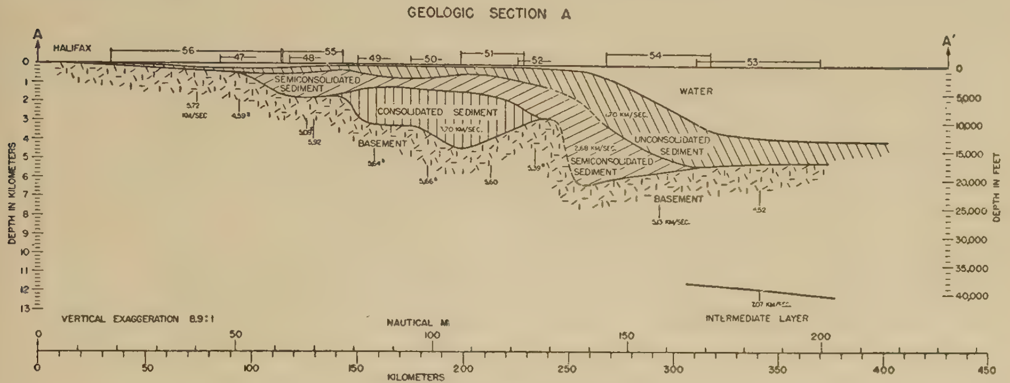
GEOLOGIC SECTION A
A
A′
HALIFAX
56
47
48
55
49
50
51
52
54
53
SEMICONSOLIDATED SEDIMENT
CONSOLIDATED SEDIMENT
3.70 KM/SEC.
BASEMENT
5.72 KM/SEC
4.59
5.08
5.92
5.64
5.66
5.60
5.39
WATER
1.70 KM/SEC.
UNCONSOLIDATED SEDIMENT
2.68 KM/SEC.
SEMICONSOLIDATED SEDIMENT
BASEMENT
5.13 KM/SEC.
4.52
7.07 KM/SEC.
INTERMEDIATE LAYER
DEPTH IN KILOMETERS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
DEPTH IN FEET
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
VERTICAL EXAGGERATION 8.9:1
NAUTICAL MI.
0
50
100
150
200
KILOMETERS
0
50
100
150
200
250
300
350
400
450

FIGURE 2.—HALIFAX SECTION

Profile 63. This profile gave a good determination of the basement on both halves and with the aid of the reverse points a good determination of the semiconsolidated sediment. At the northern station two unconsolidated sediments were measured; at the southern station only arrivals from the lower sediment could be read with assurance.

Profile 64. This profile was shot along the entrance to the Gulf of Maine at an average depth of water of 820 feet. The basement was well determined on both halves. The semiconsolidated sediment was measured only at the southern station, and the unconsolidated sediment was not measured. In the calculations a velocity of 5580 ft/sec averaged from profiles 65 and 66 was used, and the upper boundary of the semiconsolidated sediment was assumed to have zero slope.

Profile 65. This profile was shot across the entrance to the Gulf of Maine. The northern station was in 488 feet of water, and the southern station in 292 feet. The profile gave a good determination of the basement and unconsolidated sediment on both halves and with the aid of the reverse points a good determination of the semiconsolidated sediment on both halves. The topographic corrections are quite large so that confidence in the results is not as great as on adjacent profiles.

Profile 66. This profile gave a good determination of the basement, semiconsolidated sediment, and unconsolidated sediment on both halves of the profile.

Profile 67. This profile also gave a good determination of the basement, semiconsolidated sediment, and unconsolidated sediment.

Continental Slope and Continental Rise Profiles

This group consists of profiles 53, 54, 57, 58, 59, 60, 61, 62, 68, 69, and 70. The area has a more complex structure than the shelf (Figs. 2, 3, 4). A second unconsolidated sediment is measured on profiles 58, 59, 60, 61, 68, 69, and 70. The semiconsolidated sediment is thickest near the bottom of the continental slope and thins and disappears farther seaward; it is not present under profiles 53, 59, 60, and 61.

Below the basement on profiles 53, 60, 61, 69, and 70 a lower crustal layer of velocity 21,640—23,690 ft/sec (6.60–7.22 km/sec) is measured. On profile 70 a third crustal layer with a velocity 27,810 ft/sec (8.48 km/sec) is measured. Except for the lowest crustal horizon Hill (1952) obtains a similar structure on the continental rise west of Ireland. Profiles 53, 54, 57, 58, 59, 60, 61, 68, and 69 were reversed, and profiles 62 and 70 unreversed.

Profile 54. This profile gave a good determination of the basement from first arrivals and of the unconsolidated sediment from second arrivals and the reverse points on both halves. The semiconsolidated sediment was measured at the northern station only. At the southern station the experimental points show the break from basement to unconsolidated sediment first arrival. Probably there is 1000 feet or less of semiconsolidated sediment under this station, but none was included in the calculations.

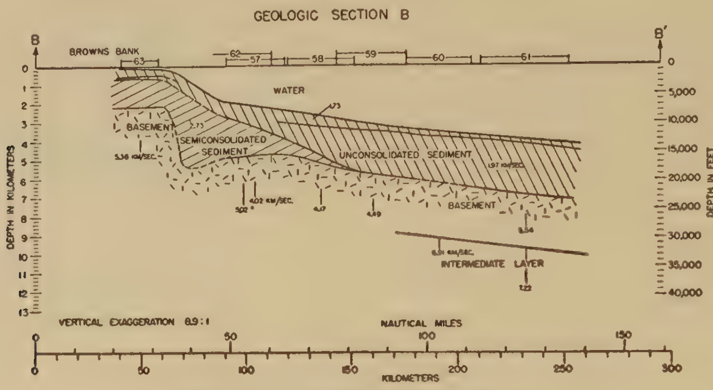
GEOLOGIC SECTION B
B
B′
BROWNS BANK
63
62
57
58
59
60
61
WATER
1.73
2.73
BASEMENT
SEMICONSOLIDATED SEDIMENT
UNCONSOLIDATED SEDIMENT
5.36 KM/SEC.
1.97 KM/SEC.
4.02 KM/SEC.
5.02
4.7
4.49
BASEMENT
5.54
6.31 KM/SEC.
INTERMEDIATE LAYER
7.22
DEPTH IN KILOMETERS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
DEPTH IN FEET
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
VERTICAL EXAGGERATION 8.9:1
NAUTICAL MILES
0
50
100
150
KILOMETERS
0
50
100
150
200
250
300

FIGURE 3.—BROWNS BANK SECTION

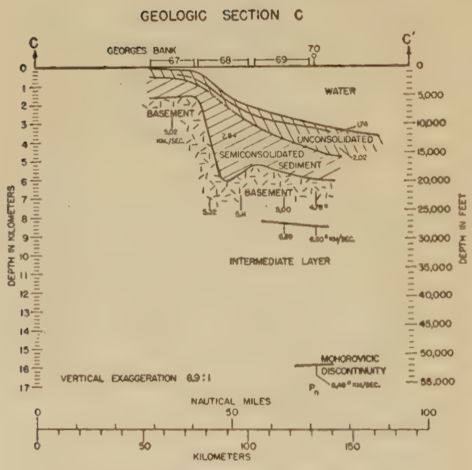
GEOLOGIC SECTION C
C
C′
GEORGES BANK
67
68
69
70
WATER
BASEMENT
5.02 KM./SEC.
2.84
1.74
UNCONSOLIDATED
2.02
SEMICONSOLIDATED SEDIMENT
BASEMENT
5.32
5.41
5.00
4.79
6.89
6.80 KM/SEC.
INTERMEDIATE LAYER
MOHOROVICIC DISCONTINUITY
8.40 KM/SEC.
P_n
DEPTH IN KILOMETERS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
DEPTH IN FEET
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
50,000
55,000
VERTICAL EXAGGERATION 8.9:1
NAUTICAL MILES
0
50
100
KILOMETERS
0
50
100
150

FIGURE 4.—GEORGES BANK SECTION

Profile 53. The unconsolidated sediment was measured from second arrivals at the northern station. The semiconsolidated sediment was not present under this profile, in agreement with the results of the southern station of profile 54. The basement is well determined at the northern station and by the reverse point and two experimental points at the southern station. The second basement is well determined at the southern station and by the reverse point and one experimental point at the northern station.

Profile 62. This profile gave a measure of the basement but not of the unconsolidated or semiconsolidated sediment. Velocities of the unconsolidated and semiconsolidated sediments and thickness of the unconsolidated sediment were taken from profile 57 for calculation of the basement on this profile. This is the poorest profile, and it is included not to add new information but only to show that it is consistent with other profiles in the same geologic locality.

Profile 57. This profile gave a good determination of the unconsolidated sediment, the semiconsolidated sediment, and the basement on both halves.

Profile 58. This profile gave a good determination of the basement. The two unconsolidated sediment layers were measured at the southern station, and the semiconsolidated sediment layer at the northern station. In the calculations the second unconsolidated sediment was assumed to be parallel to the ocean bottom and to extend under the length of profile 58. As the semiconsolidated sediment was not measured under the southern station, no thickness was included in the calculations for this station.

Profile 59. This profile gave a good determination of the first unconsolidated sediment from second arrivals at the southern station, the second unconsolidated sediment and basement on both halves. In agreement with the results of the southern station of profile 58 the semiconsolidated sediment was not present.

Profile 60. This profile is rather unsatisfactory. It gave a good determination of the second basement and the semiconsolidated sediment on both halves, but there is no determination of the upper basement or the unconsolidated sediment at either station. In the calculations a velocity of 5750 ft/sec was used for the first unconsolidated sediment from an average of profiles 57, 58, and 59. A thickness of 8030 feet for the second unconsolidated sediment and a velocity of 16,000 ft/sec for the basement from the results of profiles 59 and 61 were assumed to determine the depth of the second basement. The assumed refraction line for the upper basement is drawn on the travel time curve; with the given shot locations this refraction line would not be detected from first arrivals.

Profile 61. This profile gave a good determination of the second unconsolidated sediment, the basement, and the second basement on both halves of the profile. There is a systematic deviation of the points from a straight line for the second basement of the southern station. From the results of profiles 58, 59, and 60 a velocity of 5750 ft/sec for the first unconsolidated sediment was used in the calculations.

Profile 68. This was the only profile that directly measured the drop in the level of the basement at the edge of the continental shelf (Figs. 2, 3, and 4). The downslope of the basement from the northern station is 22° from 4100 feet to 19,300 feet. The apparent basement velocity shooting downslope is 10,710 ft/sec, and that shooting upslope is 65,750 ft/sec; they determine a true velocity of 17,460 ft/sec. It is followed by a more gentle upslope of 5° to 15,200 feet at the southern station. Even over this anomalous section the experimental values from the records, the reverse points, and the observed refraction lines are consistent among themselves as are the calculated velocities and depths.

Profile 69. This profile gave a good determination of the first and second unconsolidated sediments from second arrivals and of the semiconsolidated sediment, the basement, and the second basement from first arrivals and reverse points.

Profile 70. This is the longest profile shot over the continental rise; it extends out to a range of 40 nautical miles. It measured the basement with a velocity of 15,680 ft/sec, the second crustal layer with a velocity of 21,640 ft/sec, and a third crustal layer at a depth of 52,200 feet with a velocity of 27,810 ft/sec. Only this profile measured the third crustal layer. It is possible that the third velocity line represents a change in structure of the overlying formations and not the next lower seismic layer. This cannot be answered from an unreversed profile; but, as the profile was shot along the regional strike, it is doubtful that this line represents a change in structure. The first unconsolidated sediment was determined by second arrivals, and in the calculations velocities for the second unconsolidated sediment and the semiconsolidated sediment and thickness of the two unconsolidated sediments were taken from profile 69.

The profiles, both on the continental shelf and the continental slope and rise, present a consistent picture of the regional geology. The three sections across the continental margins show the same structure and the same changes in structure and add weight to the geophysical conclusions that might be drawn from one alone. With exception of No. 62, each of the profiles provides a good determination of its associated refraction layers; the assumptions that had to be made in the calculations on some are justified from the results of nearby profiles.

Identification of Refraction Layers

Sediment Layering

The unconsolidated sediment is present over the whole area (Fig. 5). It is generally less than 2000 feet (.6 km) thick on the continental shelf and reaches a thickness of 10,000 feet (3.0 km) on the continental rise. Along section A (Fig. 2) it thins farther seaward; sections B and C (Figs. 3, 4) did not continue out far enough to indicate this change. Under the deep ocean basin area the unconsolidated sediment is usually less than 2000 feet (.6 km) thick (Officer *et al.*, 1952, p. 791; Tolstoy *et al.*, 1953, p. 35, and Ewing *et al.*, 1954, p. 31). On the continental rise a second horizon is measured in the unconsolidated layer.

The semiconsolidated sediment is present over the outer part of the continental shelf, the continental slope, and the inner part of the continental rise (Fig. 6). It is generally less than 4000 feet (1.2 km) thick on the continental shelf and first appears about 50 nautical miles

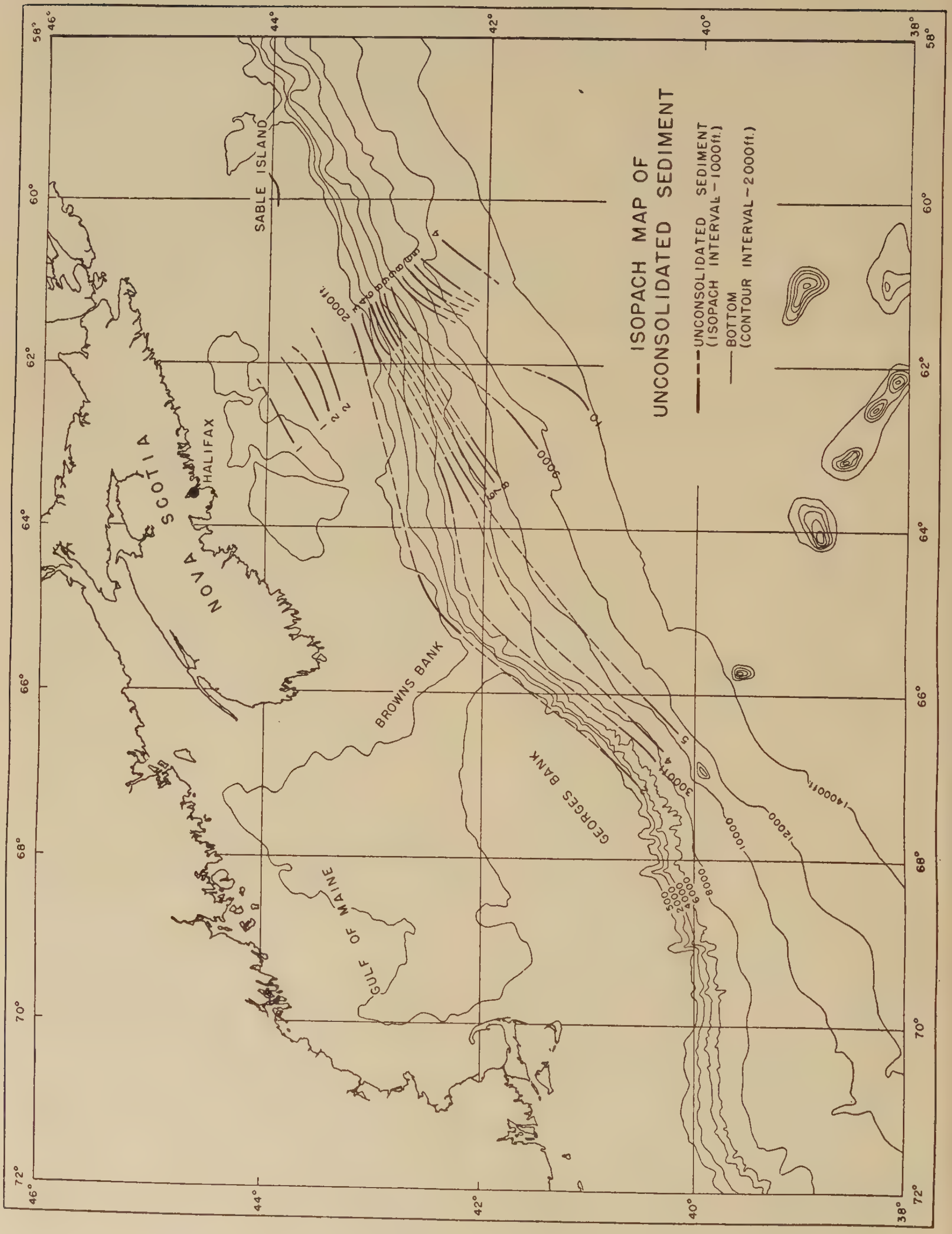
ISOPACH MAP OF
UNCONSOLIDATED SEDIMENT
UNCONSOLIDATED SEDIMENT
(ISOPACH INTERVAL - 1000ft.)
BOTTOM
(CONTOUR INTERVAL - 2000ft.)
NOVA SCOTIA
HALIFAX
SABLE ISLAND
BROWNS BANK
GEORGES BANK
GULF OF MAINE
2000ft.
3000ft.
5000
6000
8000
10000
12000
14000ft.
46°
44°
42°
40°
38°
58°
60°
62°
64°
66°
68°
70°
72°

Figure 5.—Isopach Map of Unconsolidated Sediment

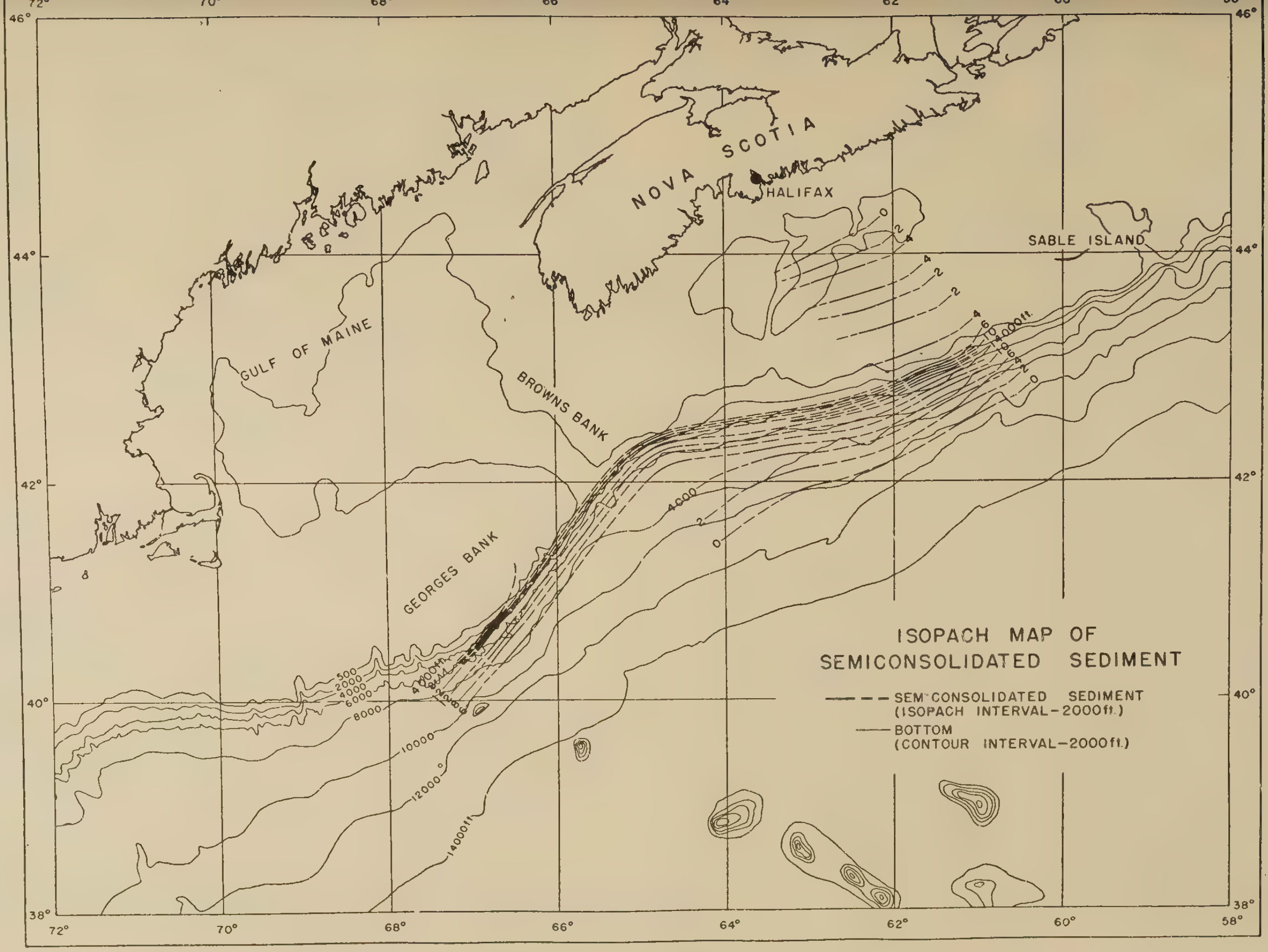
ISOPACH MAP OF
SEMICONSOLIDATED SEDIMENT
SEMICONSOLIDATED SEDIMENT
(ISOPACH INTERVAL-2000ft.)
BOTTOM
(CONTOUR INTERVAL-2000ft.)
NOVA SCOTIA
HALIFAX
SABLE ISLAND
GULF OF MAINE
BROWNS BANK
GEORGES BANK
500
2000
4000
6000
8000
10000
12000
14000ft.
4000ft.
46°
44°
42°
40°
38°
72°
70°
68°
66°
64°
62°
60°
58°

Figure 6.—Isopach Map of Semiconsolidated Sediment

(90 km) from Halifax. It attains a maximum thickness of 12,000–14,000 feet (3.7–4.3 km) at the bottom of the continental slope and thins and disappears farther seaward on the continental rise.

On profiles 49, 50, and 51 of section A, a lower sedimentary layer was found, the consolidated sediment (Fig. 2). It is present only over this limited area of the continental shelf and reaches a maximum thickness of 9500 feet (2.9 km).

The terms unconsolidated sediment and semiconsolidated sediment are retained from the earlier geophysical work on the emerged and submerged Atlantic Coastal Plain (Ewing *et al.*, 1937; 1939; 1940; 1950; Oliver and Drake, 1951). Where well data or outcrop information was available in these previous investigations, the boundary between the two seismic layers corresponded to the Raritan-Magothy boundary in the Upper Cretaceous. The unconsolidated sediment consisted of Upper Cretaceous, Tertiary, and Quaternary sediments; the semiconsolidated sediment has consisted primarily of Lower Cretaceous with a smaller thickness of Upper Cretaceous.

In another series of offshore refraction profiles in North Carolina (Skeels, 1950), which can be correlated with deep-well data (Swain, 1947; Spangler, 1950), the boundary between the two seismic refraction layers corresponds more nearly to the top of the Upper Cretaceous, with the semiconsolidated sediment consisting of Upper and Lower Cretaceous and possibly Jurassic.

From this accumulated information on other parts of the Atlantic Coastal Plain the unconsolidated sediment is identified as Upper Cretaceous, Tertiary, and Quaternary; and the semiconsolidated is identified as Cretaceous, primarily Lower Cretaceous, and possibly Jurassic. The significance of the second seismic horizon in the unconsolidated sediment over the continental rise is not known.

From its stratigraphic position, its rather limited extent, and its thickness the consolidated sediment is identified as Triassic. The interpretation is that this is another Triassic basin similar to those found along the East Coast from North Carolina to Acadia.

The only geologic information on the stratigraphy of the outer part of the continental shelf and the contental slope in this area comes from samples taken along the sides of the Georges Bank canyons. Stetson (1936; 1949) describes sandstones of Matawan and Navarro age obtained from rock-dredge tows along the sides of Oceanographer and Gilbert canyons on the edge of the continental shelf. At these locations the canyons have incised 1500–3000 feet (.46–.91 km) below the normal bottom level of 500 feet (.15 km) (Veatch and Smith, 1939, chart 4); this is sufficient to reach down to the semiconsolidated layer. He also describes dredge and core samples of Tertiary age, all of which were obtained in the canyons, and places the contact between the Upper Cretaceous and Tertiary at about 1500 feet (.46 km) below the bottom. This locates it in the unconsolidated sediment and supports the age span given above for this seismic layer. Northrop and Heezen (1951) present a photograph of an Eocene outcrop in a smaller canyon south of Cape Cod and a description of a core taken at the same time.

Crustal Layering

On the continental shelf a single high-velocity basement was measured. This basement is at the surface over central and southern Nova Scotia. It is the Meguma series, metamorphic rocks intruded by granite and gabbro of Devonian age as shown on the recent map by the Geological Survey of Canada (1949). The Meguma consists of the Halifax formation of slate and argillite and the older Goldenville formation of quartzite and slate. It is generally considered Pre-Cambrian but may be in part early Paleozoic. Their thickness has been estimated to be 30,000–35,000 feet (9–10.5 km) (Woodman, 1908, p. 109; Faribault, 1913). The results of profile 56 indicate no seismic discontinuity down to a depth of at least 45,000 feet (14 km).

The seismic velocities measured for the basement on the continental shelf are typical of those found for granites and metamorphics; and the variations in velocity, including that of profile 47, are those that might be expected in passing from granites to metamorphics or through varying degrees of metamorphism.

On the continental rise a second crustal layer was measured in the basement at an average depth of 30,000 feet (9 km) (Figs. 1–3). Its velocity of 21,640–23,690 ft/sec (6.60–7.22 km/sec) and its position below the basement identify it as the intermediate layer of continental and oceanic seismology. On the longest profile, No. 70, a third crustal layer was measured in the basement at a depth of 52,000 feet (16 km). Its unreversed velocity of 27,810 ft/sec (8.48 km/sec) identifies it as P_n of seismology and the boundary as the Mohorovičić discontinuity.

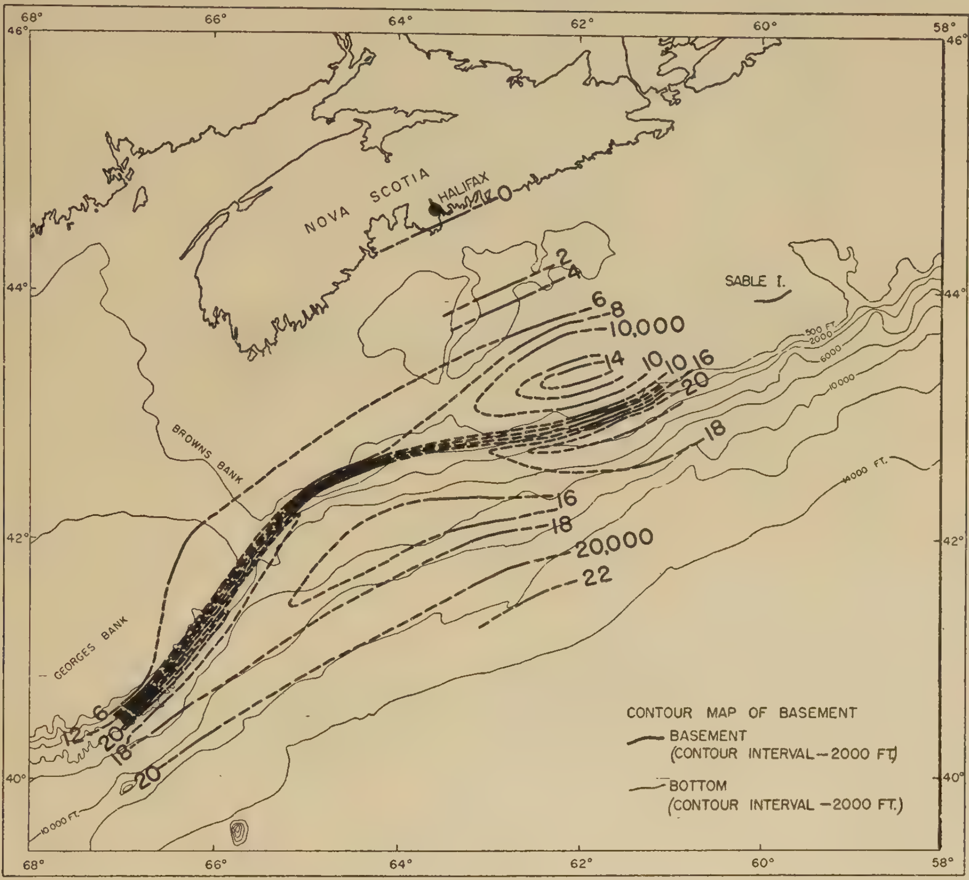
68°
66°
64°
62°
60°
58°
46°
44°
42°
40°
NOVA SCOTIA
HALIFAX
SABLE I.
BROWNS BANK
GEORGES BANK
2
4
6
8
10,000
14
10
10
16
20
18
16
18
20,000
22
6
12
20
18
20
500 FT.
2000
6000
10000
4000 FT.
10000 FT.
CONTOUR MAP OF BASEMENT
BASEMENT
(CONTOUR INTERVAL—2000 FT.)
BOTTOM
(CONTOUR INTERVAL —2000 FT.)

FIGURE 7.—CONTOUR MAP OF BASEMENT

STRUCTURE AND STRATIGRAPHY

I. One of the most prominent features of the crystalline rock basement structure is the abrupt drop in level from 5000–9000 feet (1.5–2.7 km) down to 20,000 feet (6.0 km) under the continental slope (Figs. 2, 3, 4, 7). Sections A and B did not have profiles so located as to measure this abrupt drop directly, but it is delimited by profiles 52 and 54 on section A and by profiles 63 and 57 on section B. Profile 68 of section C did measure it directly. It has a slope of 22° from 5000 feet to 20,000 feet (1.5 to 6.0 km). On each section it is followed by a more gentle upslope of the basement, and on two of the sections this latter feature is followed by a gentle downslope.

It is difficult to say whether this drop represents a large flexure, a fault or series of faults, or perhaps some other feature. No hypotheses are advanced here for its origin or its importance in regional tectonics. The purpose is to point out its presence and dimensions on these three sections across the continental margins.

II. The crystalline basement is very thick under Nova Scotia and the bordering con-

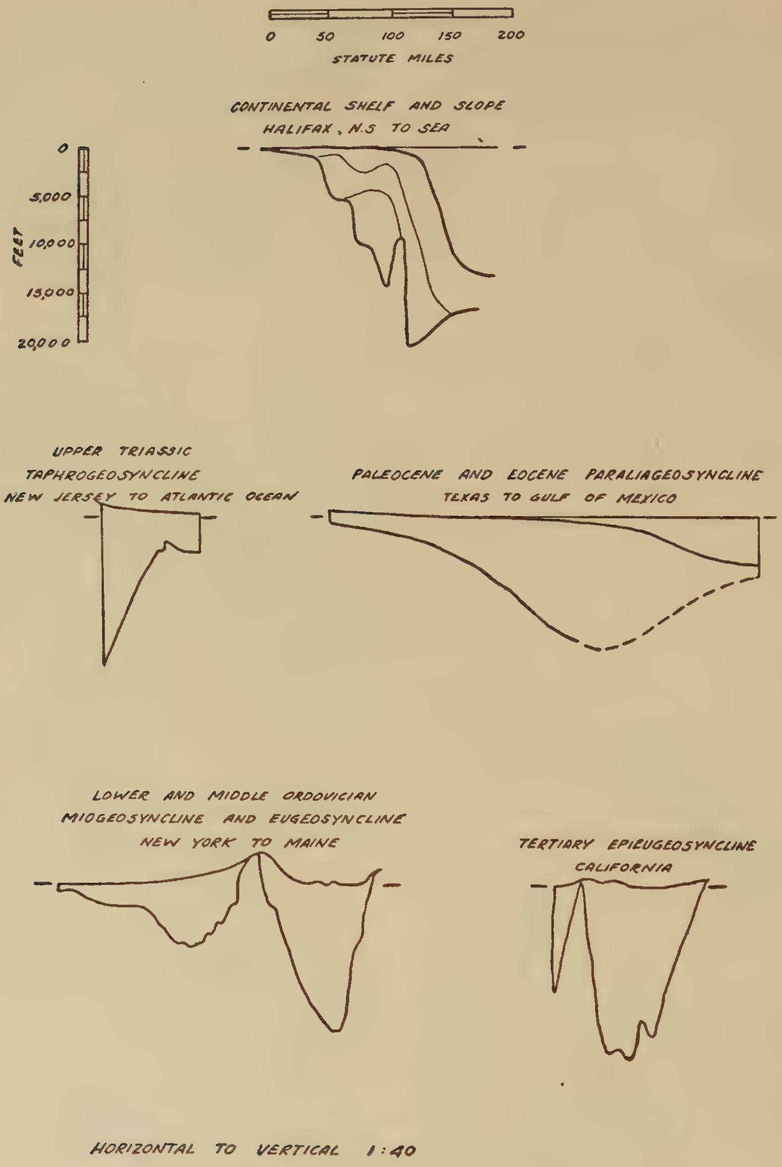
0
50
100
150
200
STATUTE MILES
CONTINENTAL SHELF AND SLOPE
HALIFAX, N.S TO SEA
0
5,000
10,000
15,000
20,000
FEET
UPPER TRIASSIC
TAPHROGEOSYNCLINE
NEW JERSEY TO ATLANTIC OCEAN
PALEOCENE AND EOCENE PARALIAGEOSYNCLINE
TEXAS TO GULF OF MEXICO
LOWER AND MIDDLE ORDOVICIAN
MIOGEOSYNCLINE AND EUGEOSYNCLINE
NEW YORK TO MAINE
TERTIARY EPIEUGEOSYNCLINE
CALIFORNIA
HORIZONTAL TO VERTICAL 1:40

Figure 8.—Geologic Sections

A comparison of the geologic section under the continental shelf, slope, and rise south of Nova Scotia with known geosynclinal sections from Kay (1951).

tinental shelf area. Woodman (1908) and Faribault (1913) estimate 30,000–35,000 feet (9–10.5 km). Profile 56 shows no discontinuity down to 45,000 feet (14 km). However, on the continental rise a lower crustal layer, the intermediate layer of seismology, is measured at an average depth of 30,000 feet (9 km), giving the basement a thickness of 10,000 feet (3 km). The results of others[1] show that the crystalline basement continues to thin and finally pinches out farther seaward on the continental rise. Under the ocean basins this upper basement is not present (Ewing *et al.*, 1954; Hersey *et al.*, 1952; Officer *et al.*, 1952).

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[1] This is quoted from as yet unpublished results of four separate refraction investigations, one by P. C. Wuenschel south of Nova Scotia, a second by J. Ewing also south of Nova Scotia, a third by J. L. Worzel south of Georges Bank, and a fourth by G. H. Sutton south of Cape Cod.

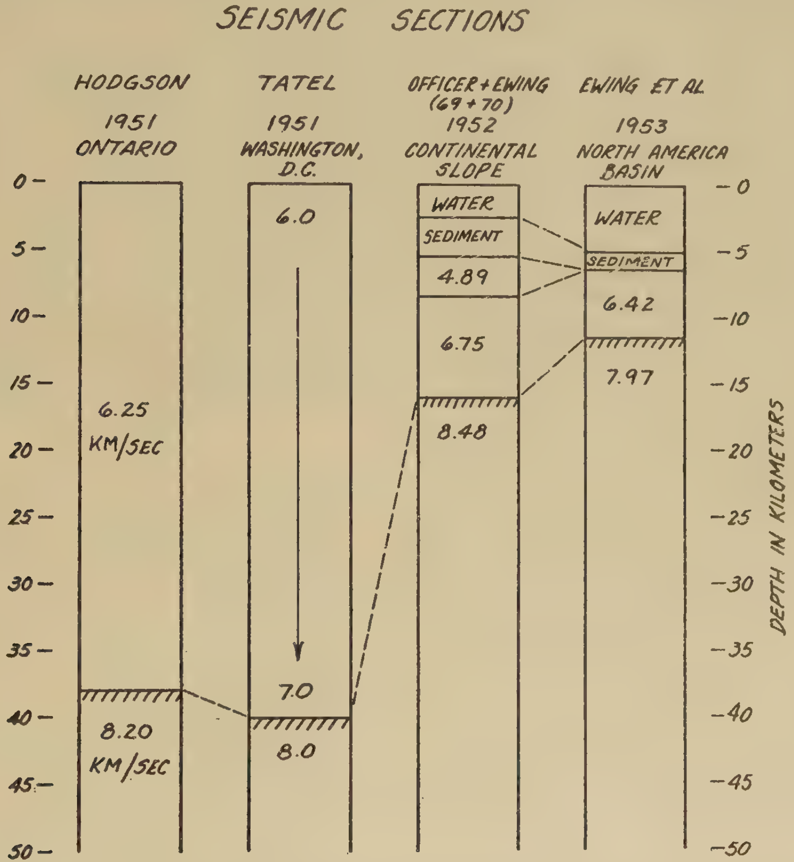
SEISMIC SECTIONS
HODGSON
1951
ONTARIO
TATEL
1951
WASHINGTON, D.C.
OFFICER + EWING (69 + 70)
1952
CONTINENTAL SLOPE
EWING ET AL
1953
NORTH AMERICA BASIN
6.25 KM/SEC
8.20 KM/SEC
6.0
7.0
8.0
WATER
SEDIMENT
4.89
6.75
8.48
WATER
SEDIMENT
6.42
7.97
0
5
10
15
20
25
30
35
40
45
50
DEPTH IN KILOMETERS

FIGURE 9.—SEISMIC SECTIONS

A comparison of crustal sections from Eastern North America across the continental margins to the North America Basin.

The basement velocities on the continental rise are in general lower than those on the continental shelf (Table 1; Figs. 2, 3, 4). The basement velocities on the continental shelf are typical of highly crystalline rocks, metamorphic rocks or granites. The basement velocities on the continental rise are down in the region of lithified sediments. Two processes are suggested as possible explanations of this phenomenon, both of which may be important. (1) The observed decrease in basement velocity represents decreasing metamorphism of the thinner basement under the continental rise farther from the main orogenic belt. (2) The lower basement velocities on the continental rise represent measurement of the sediments were being deposited seaward during the early Paleozoic when great thicknesses of sediment were being deposited landward in the Appalachian geosyncline from sources on the outer part of the continental shelf.

III. In agreement with the results of Ewing *et al.* (1950), we find that the basement does not slope simply and constantly seaward on the continental shelf. In the section from Halifax seaward, there is a great thickness of consolidated sediment of probable Triassic age in one depression and a lesser thickness of semiconsolidated sediment of probable Lower Cretaceous age in another (Fig. 2). Judging from the stratigraphic distribution of the sedimentary layers, the Triassic was deposited in a basin on the continental shelf when the basement level was higher; the Coastal Plain sediments were deposited on a platform which gradually foundered during the Cretaceous. Prior to the deposition of the unconsolidated sediment (Magothy) the area was uplifted and eroded. The same coincidence between the basement surface shoreward and the top of the semiconsolidated sediment is present on the Halifax section (Fig. 2) as was observed on the New York section (Ewing *et al.*, 1950, Fig. 1).

IV. There is a thick accumulation of Coastal Plain deposits on the continental rise. The semiconsolidated sediment reaches a maximum thickness of 14,000 feet (4.3 km) near the base of the continental slope (Fig. 6); and the unconsolidated sediment reaches a maximum thickness of 10,000 feet (3.0 km) farther out on the continental rise (Fig. 4). The younger unconsolidated sediment overlaps the semiconsolidated sediment, indicating that the area has been building out from the beginning of the Coastal Plain deposition to the present. On the continental slope the sediments, in general, are thin particularly where the continental slope is steep (Fig. 4). A comparison of the sedimentary section from Halifax to the continental rise with known continental sections taken from Kay (1951, Fig. 19) is shown in Figure 8; it is included only to demonstrate that this section is as thick and as extensive as some of the larger known sedimentary sequences.

V. The refraction data does not give a clear-cut answer as to whether the outer banks on the continental shelf—*viz*, Georges Bank, Browns Bank, and Sable Island Bank—are terminal moraines from the last glacial period or cuestas of the Coastal Plain sediment. If the banks were the expression of a terminal moraine, one would expect to pick up an additional refraction layer on the banks which would not be present shoreward off the banks. No such layer was measured along the line of profiles out of Halifax. However, there may be insufficient difference in the physical properties of the moraine and the underlying sediment to identify it as a separate refraction layer.

SEISMOLOGY

These profiles indicate the change in crustal structure from continent to ocean (Fig. 9). The upper crustal layer of continental seismology, which under Nova Scotia is the thick series of metamorphic rocks and granites, thins on the continental rise and is not present under the deep ocean basins. The intermediate layer rises from a depth of 50,000–80,000 feet (15–25 km) under the continents, to a depth of 30,000 feet (10 km) under the continental rise, and a depth of 20,000 feet (6.5 km) under the ocean basins. The Mohorovičić discontinuity is measured on one profile on the continental rise at a depth of 52,000 feet (16 km) as compared with a depth of 130,000 feet (40 km) under Eastern North America and a depth of 30,000 feet (10 km) below sea level under the ocean basins.

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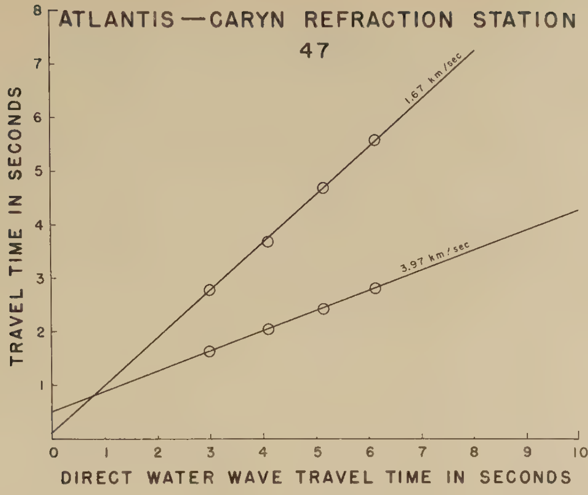
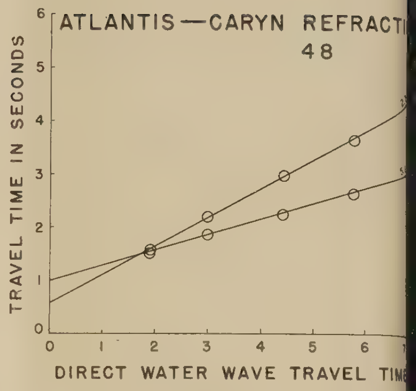
WOODS HOLE OCEANOGRAPHIC INSTITUTION, WOODS HOLE, MASS.; LAMONT GEOLOGICAL OBSERVATORY (COLUMBIA UNIVERSITY), PALISADES, N. Y.

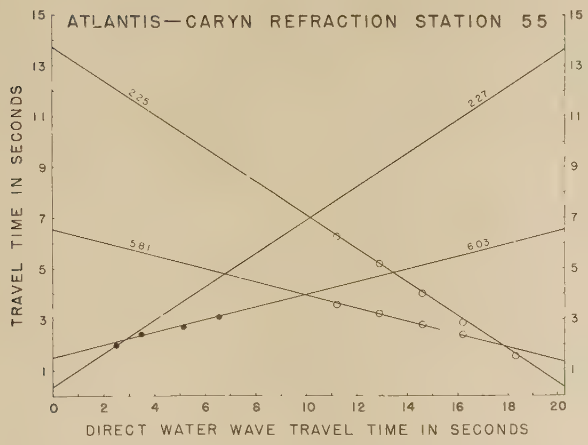
MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, APRIL 16, 1953

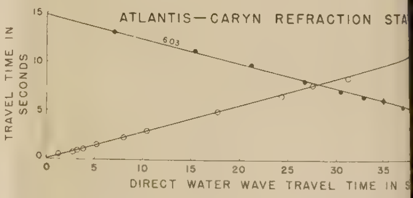
LAMONT GEOLOGICAL OBSERVATORY CONTRIBUTION NO. 112

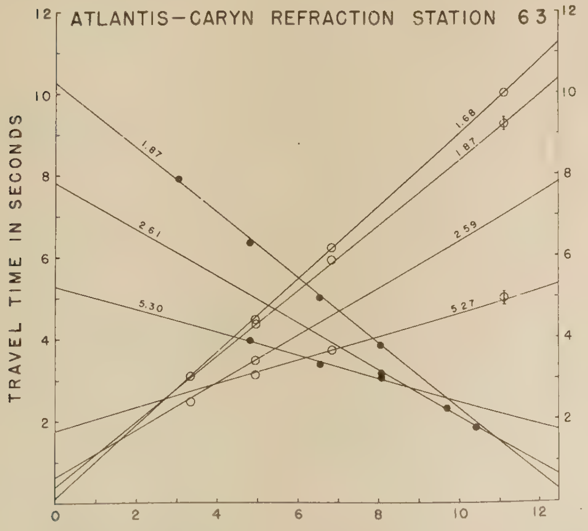
WOODS HOLE OCEANOGRAPHIC INSTITUTION CONTRIBUTION NO. 662.

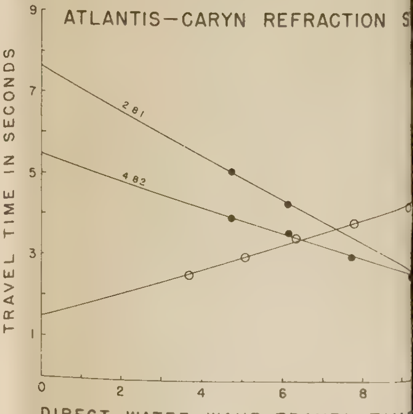

ATLANTIS—CARYN REFRACTION STATION 47
1.67 km/sec
3.97 km/sec
TRAVEL TIME IN SECONDS
DIRECT WATER WAVE TRAVEL TIME IN SECONDS
0
1
2
3
4
5
6
7
8
9
10

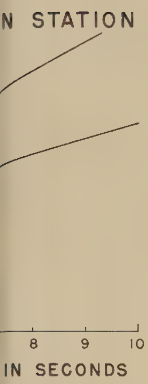

ATLANTIS—CARYN REFRACTI
48
TRAVEL TIME IN SECONDS
DIRECT WATER WAVE TRAVEL TIM
0
1
2
3
4
5
6


ATLANTIS—CARYN REFRACTION STATION 55
2.25
2.27
5.81
6.03
TRAVEL TIME IN SECONDS
DIRECT WATER WAVE TRAVEL TIME IN SECONDS
0
2
4
6
8
10
12
14
16
18
20
1
3
5
7
9
11
13
15


ATLANTIS—CARYN REFRACTION STA
6.03
TRAVEL TIME IN SECONDS
DIRECT WATER WAVE TRAVEL TIME IN S
0
5
10
15
20
25
30
35


ATLANTIS—CARYN REFRACTION STATION 63
1.87
2.61
5.30
1.68
1.87
2.59
5.27
TRAVEL TIME IN SECONDS
DIRECT WATER WAVE TRAVEL TIME IN SECONDS
0
2
4
6
8
10
12


ATLANTIS—CARYN REFRACTION S
2.81
4.82
TRAVEL TIME IN SECONDS
DIRECT WATER WAVE TRAVEL TIME
0
2
4
6
8
1
3
5
7
9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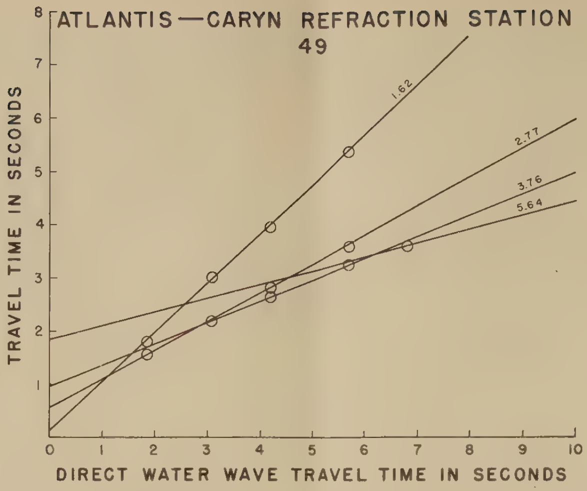
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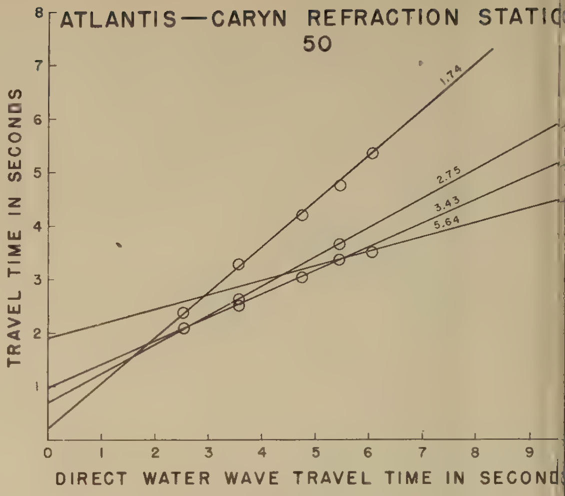
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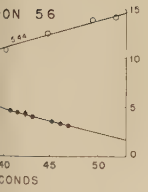
50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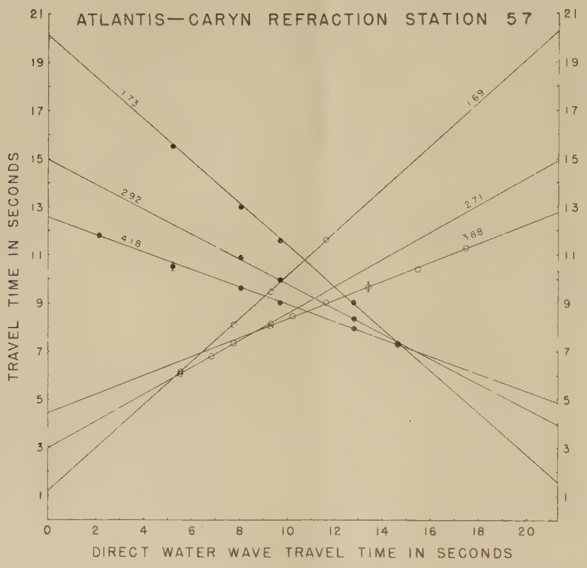
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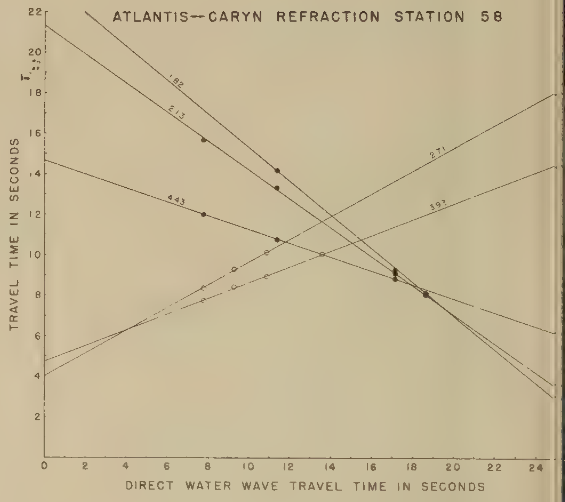
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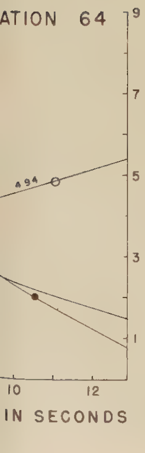
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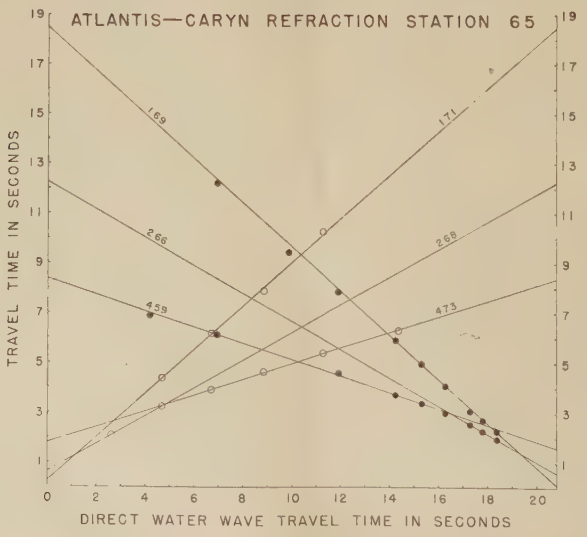
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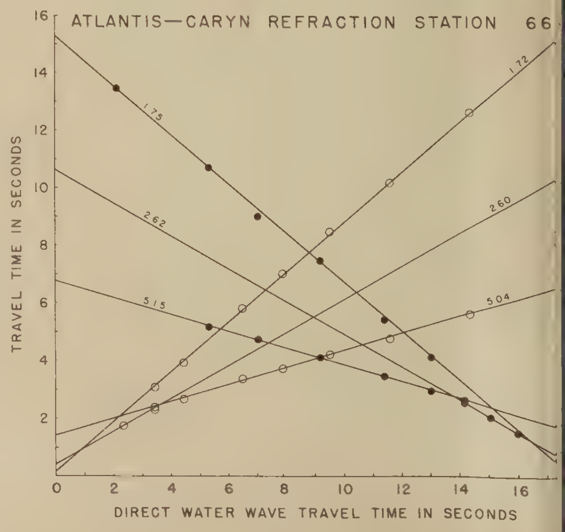
ATLANTIS—CARYN REFRACTION STATION 66

TRAVE

Contribution No. 664

ANALYSIS OF A HUGH M. SMITH OCEANOGRAPHIC SECTION FROM HONOLULU SOUTHWARD ACROSS THE EQUATOR

By

R. B. MONTGOMERY

Brown University[1] and Woods Hole Oceanographic Institution[2]

ABSTRACT

Observations from a line of stations made in February–March 1950 extending from 5° S to 21° N along meridian 158° W are analyzed, and the results are presented as distributions of sigma-*t*, salinity, oxygen, and phosphate in the vertical section. The method of analysis is partly new and is designed to achieve consistency among the several variables. This section is one of a number made in the central Pacific by the U. S. Fish and Wildlife Service.

Pacific Oceanic Fishery Investigations of the U. S. Fish and Wildlife Service executed during 1950–1952, from the research vessel Hugh M. Smith, 365 serial oceanographic stations constituting 15 or more meridional sections across the equator in the central Pacific (Cromwell, 1953). The previous temperature-salinity sections crossing the equator in this region were obtained by the Challenger (Wüst, 1929) and Carnegie (Sverdrup, et al., 1944), by Operation Crossroads (Barnes, et al., 1948) and by the Albatross (Jerlov, 1953). It is noteworthy that more meridional sections have now been made in the central Pacific than in the equatorial Atlantic or Indian oceans. Cromwell (1953) has discussed the circulation in the central equatorial Pacific by using as examples two of the new sections (172° W January–February 1950, 158° W July–August 1950). The present paper depicts a third section (158° W February–March 1950).

Opportunity for the author to take part in the analysis of these data was arranged through the courtesy of Mr. O. E. Sette, Director, and Mr. Townsend Cromwell,[3] Oceanographer, Pacific Oceanic Fishery Investigations.

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[1] Technical Report 5, Office of Naval Research contract N7onr-35811 (NR-083-050) with Brown University, Providence 12, R. I. The cost of producing Figs. 3–6 has been covered in part by this contract.

[2] Contribution No. 664 from the Woods Hole Oceanographic Institution, Woods Hole, Mass.

[3] Now at Scripps Institution of Oceanography, La Jolla, California.

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When all of the observations collected so far can be studied together, further important conclusions about the structure and circulation of the ocean can be expected, but such study will be possible only when all of the individual sections have been analyzed. The present paper has the limited objective of giving a reasonably thorough pictorial analysis of a single section.

METHOD

The data for this section consist of bathythermograms and 23 serial stations made during the interval 18 February to 2 March 1950. The stations lie within 28 miles of the meridian 158° W, the northernmost station being 25 miles from Honolulu. Bathythermograph lowerings to a nominal depth of 900 feet were made at the start and finish of each station and at 10-mile intervals between stations. The stations, spaced 60 or 120 miles apart, include serial measurements of temperature and depth by reversing thermometer; the corresponding water samples were chemically measured for salinity, oxygen, and phosphate phosphorus.

The guiding principles of the analysis are (1) to use all of the data and achieve consistency among the several variables and (2) to present the results in such a way that the relations among the several fields are readily visible. In other words, the procedure is to avoid an independent analysis of each variable (temperature, salinity, . . .).

The vertical spacing of the serial observations is too coarse to reveal the structure of the thermocline, but the bathythermograms extend down past the maximum temperature gradient. A temperature-depth curve for each station has therefore been so drawn as not only to pass through the reversing-thermometer points but also to be similar in shape to the bathythermograms for the station, as illustrated in Fig. 1.

The following characteristic curves, also shown in Fig. 1, have been drawn for each station: temperature-salinity, temperature-oxygen, and temperature-phosphate. Each curve passes through the observed points for the station, but the interpolation between points is guided by consideration of observations from adjacent stations of the section and from other stations. (After preliminary drawing of all curves, the graph of each station was superposed on the graphs of the two adjacent stations, and its characteristic curves were adjusted to give as much continuity from station to station as was permitted by the observed points.)

Thus the common scale for the four station curves is temperature; these four curves were chosen because temperature is the only vari-

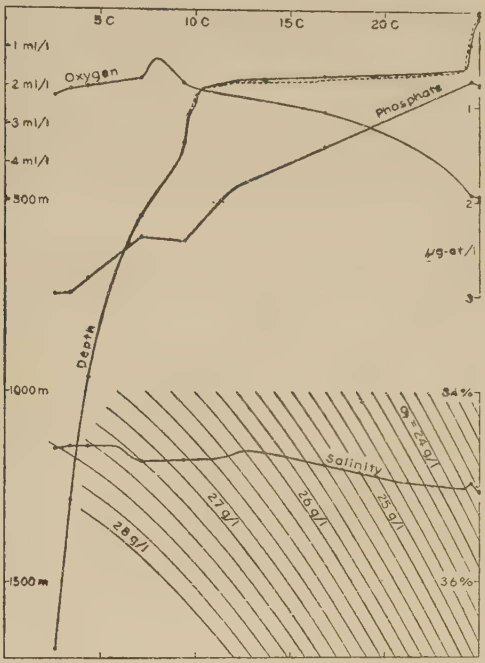

Figure 1. Depth, salinity, oxygen, and phosphate phosphorus against temperature at station 38, 3°02′N, 157°51′W, 23 February 1950. Observations by reversing thermometer and water bottle are represented by dots. One of the station's two bathythermograms is reproduced as the dashed line.

able observed continuously with depth. The temperature-depth curve and the three characteristic curves determine the continuous vertical distributions of salinity, oxygen, phosphate, and sigma-*t*.[4] The last is conveniently represented by sigma-*t* isopleths printed on the temperature-salinity diagram, as in Fig. 1.

It may be noted that only four such curves can be drawn independently. To draw in addition any of the other four vertical distributions or any of the other seven characteristic curves (temperature against sigma-*t*, oxygen against phosphate, etc.) is undesirable, because, to avoid inconsistency, each additional curve must laboriously be made to agree with those already drawn, and any subsequent adjustment of one curve involves the adjustment of one or more others.

[4] Sigma-*t* (in common use but regrettably nameless) for a point in the ocean is the excess, above one gram per milliliter, of the density of water of the same temperature and salinity but at a pressure of one atmosphere.

With all variables continuously specified for each station vertical, the next question is how best to represent the variables in two-dimensional fields for the vertical section. As with station curves, superfluous fields offer difficulty. Temperature, salinity, and sigma-*t* are interdependent, so representation of all three is undesirable because of the practical difficulty of drawing the three fields so that they agree everywhere. Two of the three and oxygen and phosphate remain to be depicted.

In order to make the relations among these four fields visible, they might all be superposed in one drawing if that were feasible, but experience indicates that no more than two fields can be adequately depicted in one drawing (except for the further addition of very simple fields). To depict all possible pairs combined from the four variables would require six drawings. It may suffice, however, if a particular variable can serve as an adequate reference, to present only the three drawings that depict the reference field in combination with each of the others.

As reference variable, temperature would have advantages, because it can be measured most easily and it can be measured continuously with depth. Sigma-*t*, however, is chosen as reference variable in the present paper. An important consideration influencing this choice is that sigma-*t* more than any other variable approaches a monotonic function of depth at any vertical and therefore has the simplest field.

With sigma-*t* already chosen, salinity is preferable to temperature as the other of these three to be represented. The reason for this choice is that sigma-*t* and temperature are so nearly parallel on a vertical section that the superposed fields are difficult to comprehend, while sigma-*t* and salinity can be superposed and remain clear.

The vertical section of sigma-*t* was constructed first. The serial observations of sigma-*t* were plotted, and the depths of each sigma-*t* isopleth at each station were plotted from the station curves. Instead of being drawn precisely through the points plotted from the station curves, the isopleths were smoothed somewhat but without violation of the observed points. The smoothing might have been achieved in an unobjectionable way by making reasonable adjustments in the station curves while keeping the vertical section consistent with the station curves.

To construct the salinity, oxygen, and phosphate fields, the serial observations and isopleth depths from station curves were plotted as for sigma-*t*. The isopleths were then drawn on a work sheet superposed on the sigma-*t* section. Some liberty was permitted in drawing the isopleths, particularly in allowing them to run more nearly parallel with the isopleths of sigma-*t*, but again the observed points were not violated.

The sigma-*t* section in Fig. 2 extends down to 1700 m so as to include all observed points, but the vertical scale is too small to show the thermocline to advantage. Figs. 3–6 show the upper 500 m of the four fields on larger vertical scale. The distributions of salinity, oxygen, and phosphate below 500 m are omitted.

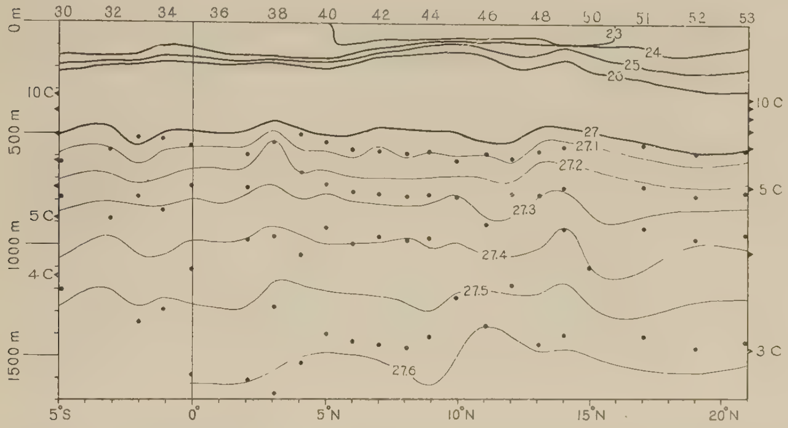

Figure 2. Sigma-*t* in grams per liter. Temperature at ends of section is shown by a tooth for each degree centigrade up to 10 C. Observation points below 500 m are shown by dots; those above 500 m appear in Fig. 3. Station numbers at top. Vertical exaggeration 927.

The field of sigma-*t* alone (Fig. 3) is included in addition to the minimum three drawings (Figs. 4–6). One practical advantage of this repetition is that some of the details of the thermocline shown in Fig. 3 could be omitted from Figs. 4–6.

Although the temperature field is not shown, a rough indication of temperature is provided by marking the depth of each whole degree centigrade at both ends of the section.

The bathythermograms between stations provide valuable information that can be incorporated in sigma-*t* sections. All isothermal layers from all bathythermograms were drawn as vertical lines on the work sheet. These vertical lines served as barriers forbidden to be crossed by the sigma-*t* isopleths, which therefore either avoid vertically isothermal regions altogether or traverse them vertically.

The thermocline on bathythermograms between stations should have been utilized also, but actually it was not. A suitable procedure would be to use all bathythermograms in constructing a temperature section, which would then serve as a guide on which the sigma-*t*

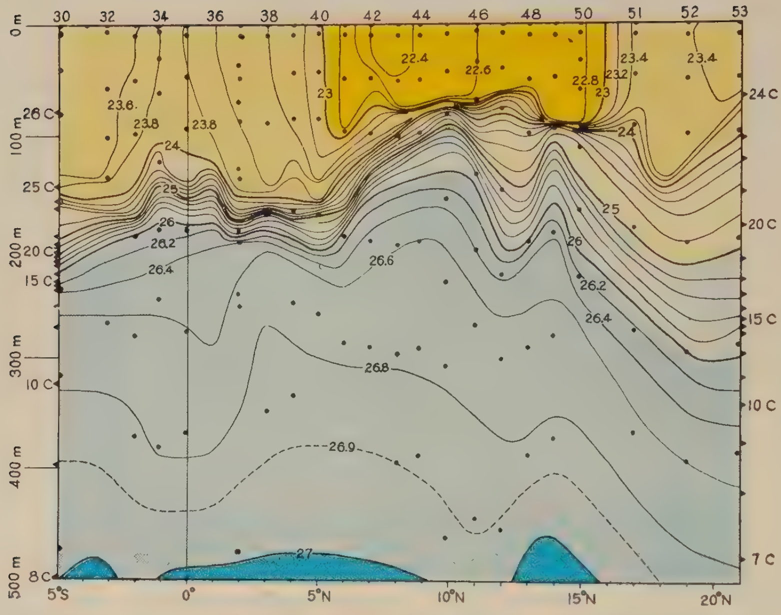

Figure 3. Sigma-*t* in grams per liter. Temperature at ends of section is shown by a tooth for each degree centigrade. Vertical exaggeration 4633.

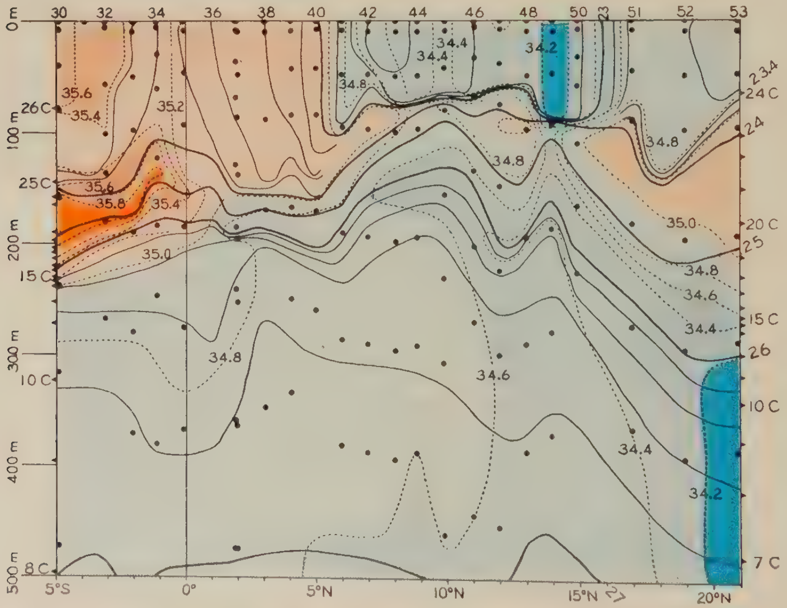

Figure 4. Salinity in per mille. Most of the sigma-*t* isopleths are repeated from Fig. 3 and are labeled at right in grams per liter.

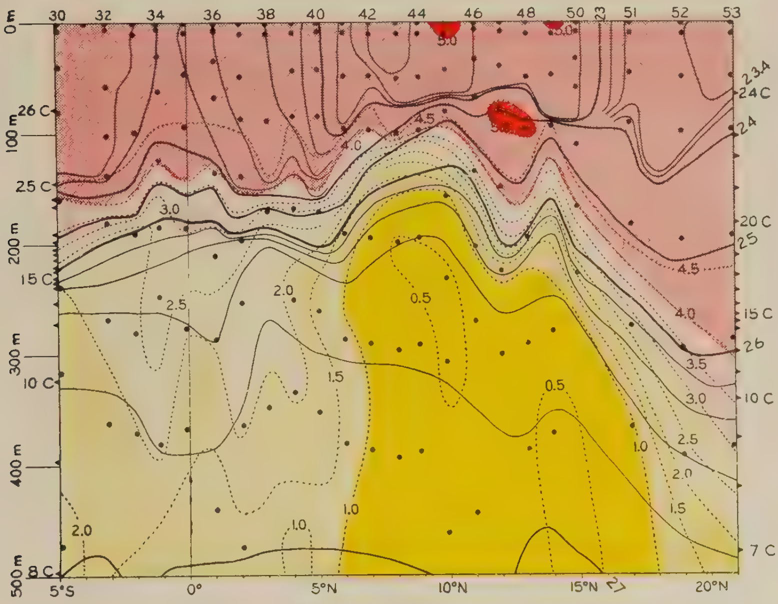

Figure 5. Oxygen in milliliters (NTP) per liter.

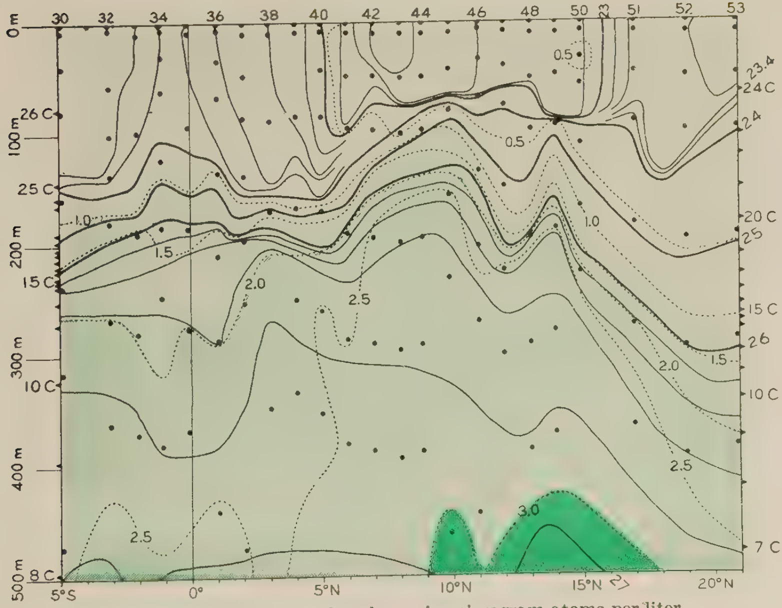

Figure 6. Phosphate phosphorus in microgram-atoms per liter.

section could be superposed while constructing the isopleths. This procedure would place the latitudes of maxima and minima in depth of sigma-*t* isopleths more precisely than they are shown in the present drawings.

DISCUSSION

It is clear from Fig. 3 that bathythermograms in conjunction with rather coarse vertical spacing of serial observations reveal much sharper density gradients and more detail than would the serial observations alone. The horizontal detail also would have been increased if the close spacing of the bathythermograms had been fully utilized. Furthermore, it is clear that, if the salinity, oxygen, and phosphate fields were constructed quite independently of the density field, they would come out markedly different from those in Figs. 3–6, and the four fields would be inconsistent.

Some features of the section may be mentioned, although the primary purpose has been accomplished by presenting the method and pictorial results of the analysis.

Typical of equatorial waters, there is great contrast between the high degree of homogeneity of the surface layer and the large gradients of the thermocline. Bathythermograms are essential for revealing the full magnitude of this contrast.

The sloping thermocline from 5° N to 10° N marks the zone of the Equatorial Countercurrent. The greatest density gradients occur in the upper part of the thermocline near the northern edge of the Countercurrent.

A trough at 12½° N and a ridge at 14° N in the sigma-*t* isopleths of the lower part of the thermocline mark an unusually large disturbance within the North Equatorial Current. At 14° N the layer containing the salinity maximum appears to be absent, as though pinched off, although the water samples are too widely spaced to determine the salinity distribution with certainty.

The salinity maximum in the thermocline south of the equator seems to stop abruptly near the equator. The presence of the maximum proves that there is no transfer of water between the surface layer and the water beneath the maximum. Where the maximum is absent, as it appears to be from 1° N to 5° N, this proof is lacking.

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Contribution No. 665

THE GROWTH OF SEA-SALT PARTICLES BY CONDENSATION OF ATMOSPHERIC WATER VAPOR

By C. H. Keith and A. B. Arons

Woods Hole Oceanographic Institution[1,2]

(Manuscript received 3 August 1953)

ABSTRACT

Measurements of the rate of growth of sea-salt particles have been made when the particle is shifted from an environment of dry air to one of relative humidity between 80 and 100 per cent. For particles ranging in mass from 10^{-9} to 2×10^{-8} gram, agreement is found with growth times predicted by an equation which principally differs from previous derivations in that empirical vapor-pressure data are utilized. The growth time is observed to be independent of ventilation at air speeds less than 30 to 40 centimeters per second.

The growth equation was reintegrated under variable humidity and temperature conditions corresponding to rates of lift observed in the atmosphere. The curves thus obtained approximately trace the growth of sea-salt particles rising from the sea surface to cloud base.

1. Introduction

Accurate information about the growth of microscopic sea-salt particles by condensation of water vapor is necessary for the evaluation of the role of these particles in the formation of clouds, rain and fog. Condensational growth has been the subject of theoretical investigations by Howell (1949), Kraus and Smith (1949), Squires (1952), Best (1951; 1953) and others. In these investigations, the use of Raoult's law, and of various other approximations, made the accuracy of the resulting growth calculations doubtful.

Since Woodcock (1949; 1952) has demonstrated the presence of large sea-salt nuclei (10^{-8} to 10^{-12} g) in the atmosphere, and since his subsequent investigations indicate that these nuclei may possibly play a dominant role in the mechanism of rain production in warm clouds, it was felt that a careful experimental and theoretical investigation of the growth of droplets formed on such nuclei was desirable. The application of the derived growth equation under variable temperature and humidity conditions was also considered, so that a droplet-size spectrum in sub-cloud regions may be obtained from the resultant growth curves and from Woodcock's salt particle distributions.

2. The growth equation

In previous investigations, Howell (1949) and others were concerned with nuclei having masses of 10^{-13} to 10^{-20} g, which were growing in an atmosphere supersaturated with water vapor. With such small particles, the effect of surface tension on the droplet vapor-pressure was of the same or greater magnitude than the lowering caused by dissolved salts. For droplets of the size with which we are here concerned, surface tension effects are negligible, and the humidity range of interest is that below 100 per cent. During much of its growth, the droplet consists of a concentrated solution of sea salt, for which the vapor pressure deviates appreciably from that given by Raoult's law. For this reason, the vapor-pressure measurements of Arons and Kientzler (1954) have been empirically incorporated in the theoretical part of our investigation.

If a sea-salt particle is introduced into an atmosphere of sufficiently high relative humidity, the particle will grow to a droplet by condensation of water vapor. Growth will continue until an equilibrium size is reached, when the droplet vapor-pressure is equal to that of water in the surrounding atmosphere. The growth rate depends primarily upon the vapor-pressure gradient between the droplet surface and ambient air. This gradient determines the rate of vapor diffusion to the saline surface of the droplet, and consequently the rate of condensation. The heat liberated by condensation is initially stored in the droplet, hence elevating its temperature. This has the dual effect of reducing the vapor gradient and of allowing heat conduction away from the droplet. In the following derivation it is assumed that a steady-state condition, in which the vapor and thermal gradients are interdependent, is rapidly obtained. It is also assumed that the classical laws of diffusion and heat conduction apply to these droplets. Howell (1949) has discussed the limits of applicability of these laws, and concludes that kinetic-theory correction need not be made for droplets of radius greater than 6 to 8 μ.

It is further assumed that the effect of other droplets upon the gradients around a given droplet is negligible, and that mass divergence is also negligible in the initial transport equations. These assumptions have also been considered by Langmuir (1944) and Howell (1949), and found to be reasonable.

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[1] Contribution No. 665 from the Woods Hole Oceanographic Institution. This study was supported by the Office of Naval Research, under Contract Number Nonr-798(00) (NR-085-001).

[2] Mr. Keith's present affiliation: Liggett and Myers Tobacco Company.

The well-known rate equations are[3]

$$\frac{dq}{dt} = \begin{matrix}\text{time rate of mass transport}\\ \text{of water vapor to droplet}\end{matrix} = 4\pi D(R')^2\left[\frac{d\rho}{dR'}\right], \quad (1)$$

$$\frac{dQ_1}{dt} = \begin{matrix}\text{time rate of heat transport}\\ \text{away from droplet}\end{matrix} = 4\pi k(R')^2\left[\frac{dT}{dR'}\right] \quad (2)$$

and

$$\frac{dQ_2}{dt} = \begin{matrix}\text{time rate of heat storage}\\ \text{in droplet}\end{matrix} = mc_p\frac{dr}{dt}\frac{dT}{dr}. \quad (3)$$

Integration of (1) and (2) over space leads to the usual expressions for the thermal and vapor-density gradients between r, the droplet radius, and a point infinitely removed from r. It is also assumed that all the vapor which diffuses to the droplet is condensed thereon, *i.e.*, that the accommodation coefficient is unity. Another assumption is that the effect of heat storage upon droplet growth is small, thus permitting the approximation of dT/dr in (3) by $(T - T_1)/(r - r_1)$, where T_1 and r_1 are the initial temperature and radius of the droplet. Substitution of the thermal and vapor gradients in the above equations leads to the heat- and vapor-balance equation,

$$LD(\rho_1 - \rho) = \left(k + \frac{\rho_s c_p r}{3\delta}\frac{dr}{dt}\right)(T - T_1), \quad (4)$$

where

$$\delta \equiv 1 - (r_1/r).$$

The vapor-transport equation (1) may be transformed into the well known form which gives the time-rate-of-change of droplet radius in terms of the vapor-density,

$$r\frac{dr}{dt} = \frac{D}{\rho_s}(\rho_1 - \rho). \quad (5)$$

Combination of this with (4), and conversion of vapor density to vapor pressure by means of the ideal gas law, yield

$$r\frac{dr}{dt} = \frac{DM}{\rho_s R}\left(\frac{P_1}{T_1} - \frac{P}{T}\right) = \left(\frac{k}{\rho_s L} + \frac{c_p r}{3L\delta}\frac{dr}{dt}\right)(T - T_1). \quad (6)$$

The Clapeyron equation, in its integrated form, can be used to describe the variation of droplet vapor-pressure, P, with droplet temperature, T:

$$\log\frac{P}{P_2} = \frac{LM}{R}\left(\frac{1}{T_1} - \frac{1}{T}\right). \quad (7)$$

Since the pressure and temperature differences are small, (7) may be approximated by

$$P = P_2\left[1 + \frac{LM}{RT_1^2}(T - T_1)\right]. \quad (8)$$

Combination of (8) with (6) leads to a growth equation containing readily measureable variables,

$$r\frac{dr}{dt} = \frac{DM}{\rho_s R}\left[\frac{P_1}{T_1} - P_2\left(1 + \frac{\rho_s L^2 M}{k\alpha R T_1^2}r\frac{dr}{dt}\right) \times\left(T_1 + \frac{\rho_s L}{k\alpha}r\frac{dr}{dt}\right)^{-1}\right], \quad (9)$$

where

$$\alpha \equiv 1 + \frac{c_p\rho_s}{3k\delta}r\frac{dr}{dt},$$

which, upon rearrangement and solution of the resulting quadratic equation, gives

$$r\frac{dr}{dt} = B(P)\left\{1 \pm \left[1 + \frac{C(P)}{B^2(P)}\right]^{\frac{1}{2}}\right\}, \quad (10)$$

where

$$B(P) = \frac{DM}{2\rho_s RT_1}\left(P_1 - \frac{ML\beta}{RT_1\gamma}P_2 - \frac{RT_1^2k}{DML\gamma}\right),$$

$$C(P) = \frac{DMk}{RL\rho_s^2\gamma}(P_1 - P_2),$$

$$\gamma \equiv 1 + \frac{c_p T_1}{3L\delta} \quad \text{and} \quad \beta \equiv 1 + \frac{c_p RT_1^2}{3ML^2\delta}.$$

Examination of (10) reveals that $B(P)$ is inherently negative, while the sign of $C(P)$ depends upon the sign of the vapor-pressure difference, $P_1 - P_2$. To give $r\,dr/dt$ the same sign as the pressure difference, *i.e.*, positive for growth, negative for evaporation, the negative branch of (10) must be utilized, and the positive branch has no physical significance.

P_1 can be expressed as the product of relative humidity and saturation vapor-pressure, P_0, while P_2 can be considered as the difference between P_0 and the vapor-pressure lowering ΔP. ΔP is, of course, a function of temperature and concentration of the droplet.

Droplet concentration is thus indirectly introduced into (10); consequently, any explicit dependence upon particle weight may be removed from the growth equation by introduction of a concentration variable in place of r. Such a variable is the "scaled" radius,

$$\sigma \equiv rm_s^{-\frac{1}{3}}, \quad (11)$$

and this requires the further substitution of a "scaled" time,

$$\tau \equiv tm_s^{-\frac{2}{3}}, \quad (12)$$

to maintain the left side of (10) unvaried.

The right-hand side of (10) may be sufficiently well approximated by the leading term of the infinite-series expansion, since the second term is found to be less than 0.5 per cent of the leading term. With these changes (10) becomes,

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[3] See the Appendix for a list of the symbols used throughout this paper.

$$\left\{\frac{\rho_s RT_1}{DM}+\frac{ML^2\rho_s\beta'}{RT_1^2k}[P_0-\Delta P(\sigma)]-\frac{L\rho_s\gamma'}{kT_1}HP_0\right\}$$
$$\times\{(H-1)P_0+\Delta P(\sigma)\}^{-1}\sigma\, d\sigma$$
$$-\frac{c_p\rho_s}{3k}\frac{\sigma_1}{\sigma-\sigma_1}\sigma\, d\sigma=d\tau, \quad (13)$$

where

$$\beta'\equiv 1+\frac{c_pRT_1^2}{3ML^2} \quad \text{and} \quad \gamma'\equiv 1+\frac{c_pT_1}{3L}.$$

The term containing $\sigma_1/(\sigma-\sigma_1)$ is found upon integration to be negligible at all values of σ, except where $\sigma\approx\sigma_1$. However, the very early stages of growth contribute very little to the integral, and other approximations as serious as the neglect of this term have already been invoked in this region. To simplify the integration of (13), this term is not included.

Before proceeding further with the development of the growth equation, we must formulate an empirical vapor-pressure equation for $\Delta p(\sigma)$. σ is given in terms of the density and concentration of the solution by the following relation:

$$\sigma=\left\{\frac{3}{4\pi\rho_s}\left(1+\frac{m_w}{m_s}\right)\right\}^{\frac{1}{3}}. \quad (14)$$

In (14), the mass of water, m_w, equals 1000−1.805 Cl, and the mass of salt, m_s, equals 1.805 Cl, the chlorinity units being parts per thousand. Arons and Kientzler's (1954) smoothed vapor-pressure data are plotted against σ in fig. 1, and the following empirical representation is obtained:

$$\Delta p(\sigma)=0.146\, P_0\sigma^{-3.35}. \quad (15)$$

Unfortunately, the non-integral power of σ in $\Delta P(\sigma)$ prohibits analytical integration of (13) at any value of the humidity, H, besides 1.0. At this value, the integration yields the expression

$$1.28\left(\frac{\rho_s RT_1}{DMP_0}+\frac{ML^2\rho_s\beta'}{RT_1^2k}-\frac{L\rho_s\gamma'}{kT_1}\right)\sigma^{5.35}$$
$$-\frac{ML^2\rho_s\beta'}{2RT_1^2k}\sigma=\tau+C. \quad (16)$$

Since it is necessary to integrate the growth equation numerically at other humidities, further simplification of (13) is desirable, to reduce the labor involved. The difference between HP_0 and $P_0-\Delta P(\sigma)$ is normally small; hence, it is convenient to introduce

$$\ln\frac{HP_0}{P_0-\Delta P(\sigma)}\approx[(H-1)P_0+\Delta P(\sigma)]/\bar{P}.$$

where $\bar{P}$ = the mean of the ambient and droplet vapor-pressures. Also, by ignoring the heat storage within the droplet and calling the ratios of $HP_0/\bar{P}$

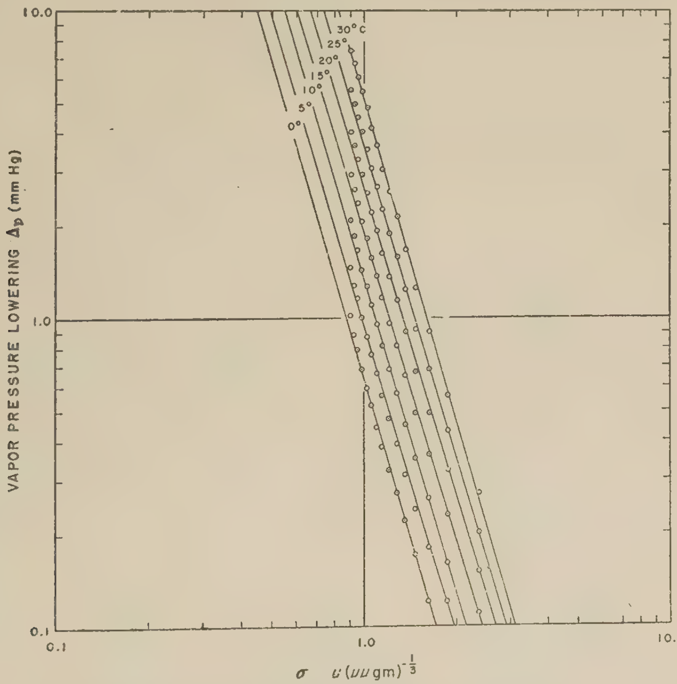

FIG. 1. Arons and Kientzler's vapor-pressure lowerings for sea-salt solutions, as a function of σ. Lines are calculated by the equation $\Delta P(\sigma)=0.146\, P_0\sigma^{-3.35}$.

TABLE 1. Values of factor A in (17) at various temperatures.

T(C)	A (μ^2/sec)
0	55
10	83
20	114
30	143

and $P_0[\Delta P(\sigma)/\bar{P}]$ unity, we may reduce (13) to

$$\sigma\, d\sigma/d\tau = -A \ln[(1 - 0.146\, \sigma^{-3.35})/H] \qquad (17)$$

where

$$A \equiv \left(\frac{\rho_s R T_1}{D M \bar{P}} + \frac{\rho_s M L^2}{R T_1^2 k} - \frac{\rho_s L}{k T_1}\right)^{-1}$$

Substitution of values of the indicated constants leads to values of A which are relatively insensitive to changes in $\bar{P}$. For example, at 25C, $\bar{P}$ can vary from 19 to 24 mm Hg, which amounts to a variation in A of ±0.7 per cent about the mean. However, A is quite temperature sensitive, as is shown in table 1.

Equation (17) is essentially the same as Howell's (1949), except that surface-tension effects have been neglected, and an empirical vapor-pressure function introduced.

The upper limit of σ, or its equilibrium value, is defined by both (13) and (17). In each equation, τ approaches infinity asymptotically as $0.146\ \sigma^{-3.35}$ approaches $1-H$. Comparison of values obtained by

$$\sigma_{\mathrm{eq}} = \left(\frac{0.146}{1-H}\right)^{0.299} \qquad (18)$$

with those calculated by the formula developed by Wright (1936) reveals that his values are from 3 to 14 per cent greater than those computed by (18). The reason for this discrepancy is contained in Wright's (1936) use of a constant "hydroscopic factor" in Raoult's law. McDonald (1953) has discussed the use of such factors, which account for the ionic character of salt solutions, and he demonstrates that considerable error may be introduced either by neglecting them entirely or by not considering their variation with concentration.

An additional vapor-pressure function must be derived to replace (15) during the initial, brief period of growth from crystalline mass to droplet of saturated solution. Thompson (1932) reports that bischofite ($MgCl_2 \cdot 6H_2O$) is the final salt crystallized upon evaporation of sea water. Therefore, it is to be expected that the first water condensed upon a desiccated sea-salt particle will form a film of solution saturated with magnesium chloride. It is assumed herein that the vapor pressure during crystal growth arises linearly from that above a saturated magnesium-chloride solution to that above a saturated sea-salt solution.

TABLE 2. Scaled time for growth of sea-salt particles to droplets of saturated solution, as a function of relative humidity. (T_1 = 25C.)

H	τ_0[sec $(\mu\mu g)^{-2/3}$]
0.85	0.0077
0.90	0.0057
0.92	0.0052
0.94	0.0048
0.96	0.0044
0.98	0.0041
0.99	0.0040
1.0	0.0038

TABLE 3. Comparison of (16) with (17) at H = 1.0 (excluding τ_0 for growth of crystal).

σ	τ(16) T_1=25C	τ(17) T_1=25C	τ(17) T_1=30C	τ(17) T_1=20C
[$\mu(\mu\mu g)^{-1/3}$]		[sec $(\mu\mu g)^{-2/3}$]		
0.9	0	0	0	0
1.0	0.0036	0.0039	0.0035	0.0045
1.2	0.0184	0.0196	0.0176	0.0222
1.4	0.0501	0.0525	0.0471	0.0595
1.6	0.111	0.114	0.103	0.130
1.8	0.215	0.222	0.199	0.252
2.0	0.384	0.396	0.355	0.449
2.2	0.648	0.665	0.596	0.754

From Arons' and Kientzler's (1954) data on the concentration of saturated sea-salt solutions, and Higashi's (1931) density data, a value of σ of 0.90 $\mu\ (\mu\mu g)^{-1/3}$ is calculated by (14) at saturation. The density of sea salt, computed from Thompson's (1932) data, is 2.06 g/cm³. The value of σ calculated from this density is $0.50\mu\ (\mu\mu g)^{-1/3}$. These values, when combined with the humidities existing over saturated $MgCl_2$ and sea-salt solutions (33 and 79 per cent, respectively), yield the following expression for the vapor-pressure lowering during the change from crystal to saturated droplet, i.e., for the range $0.50 < \sigma < 0.90$:

$$\Delta p(\sigma) = p_0(1.25 - 1.16\, \sigma). \qquad (19)$$

Substitution of (19) into (13), evaluation of the constants, and integration, result in the following equation, which gives the scaled time, τ_0, for growth

Table 4. Values of τ, sec $(\mu\mu gm)^{-2/3}$, for growth of sea salt particles to selected values of σ, $\mu\ (\mu\mu gm)^{-1/3}$, at selected humidities, T = 25 C. All values computed by equation (17)

σ	Relative Humidity 0.85	0.90	0.92	0.94	0.96	0.98	0.99	1.0
.90	.0077	.0057	.0052	.0048	.0044	.0041	.0040	.0038
.92	.0101	.0069	.0062	.0057	.0052			
.94	.0136	.0084	.0074	.0067	.0061			
.96	.0192	.0102	.0088	.0078	.0070			
.98	.0316	.0123	.0104	.0092	.0082			
1.00		.0150	.0124	.0107	.0094	.0085	.0081	.0077
1.05		.0256	.0190	.0157	.0134	.0120	.0111	.0105
1.10		.0560	.0302	.0227	.0186	.0162	.0149	.0140
1.15			.0535	.0337	.0257	.0216	.0196	.0182
1.20				.0510	.0353	.0283	.0255	.0234
1.25				.0854	.0488	.0368	.0326	.0296
1.30				.323	.0676	.0475	.0414	.0370
1.35					.0975	.0610	.0518	.0459
1.40					.150	.0782	.0645	.0563
1.45					.314	.100	.0802	.0685
1.50						.129	.0992	.0827
1.55						.167	.122	.0992
1.60						.218	.150	.118
1.65						.291	.184	.140
1.70						.400	.224	.165
1.75						.603	.274	.193
1.80						1.32	.335	.225
1.85							.410	.262
1.90							.504	.303
1.95							.624	.348
2.00							.782	.399
2.05							1.00	.457
2.10							1.32	.520
2.15							1.85	.591
2.20							3.35	.669

to saturated sea-salt solution at 25C:

$$\tau_0 = (0.0013 + 0.0043\,H) \times \left[-0.46 + (H + 0.25)\ln\frac{H - 0.33}{H - 0.79}\right] - 0.0017. \quad (20)$$

Values of τ_0 computed by (20) are listed in table 2.

The numerical integration of the growth equation (17) was performed by the usual trapezoidal area method. The results of the integrations are presented in tables 3 and 4, and fig. 2.

The close agreement between the results obtained

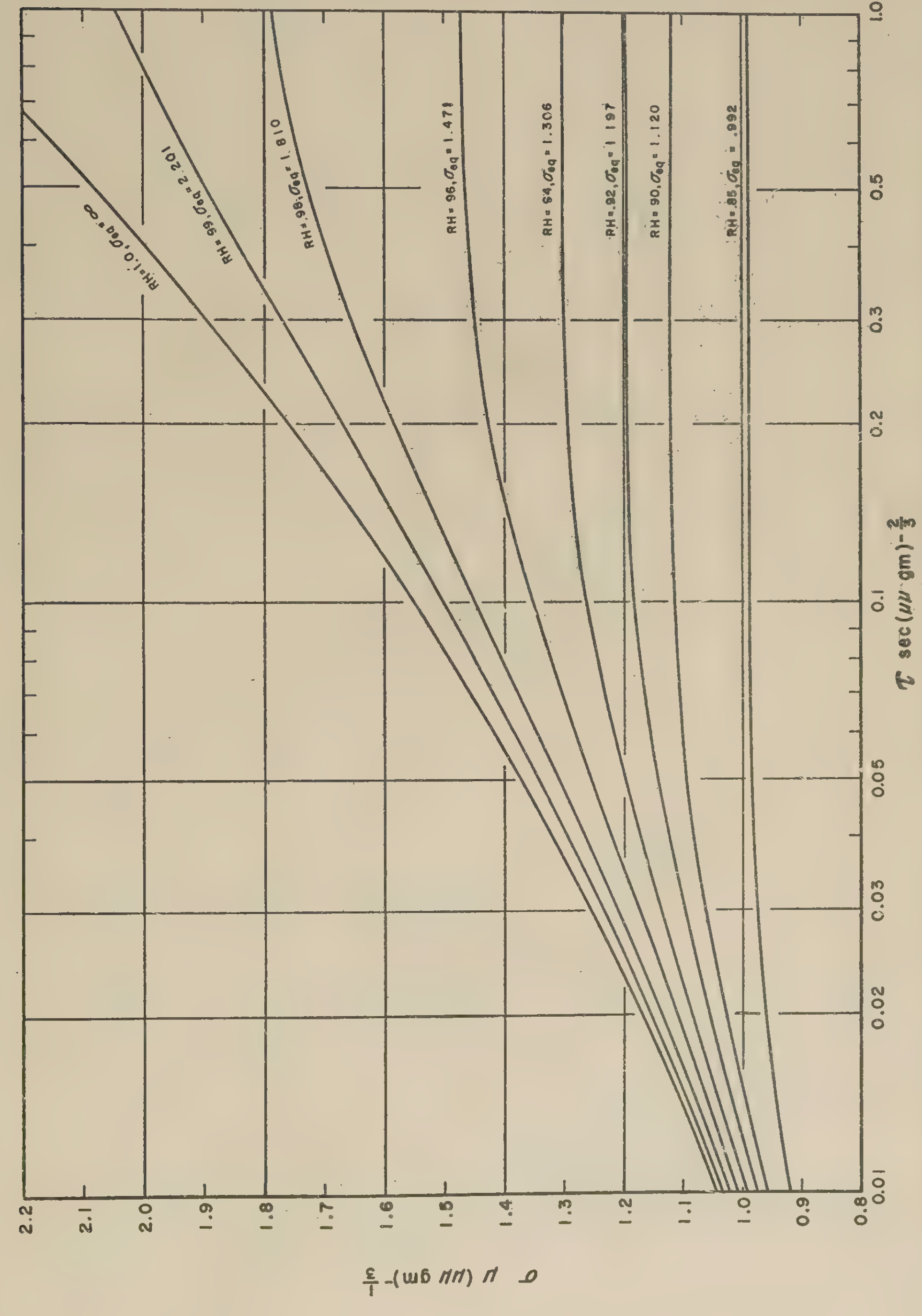

FIG. 2. Sea-salt particle-growth curves calculated by (17) at various fractional humidities and dry-bulb temperature of 25C. Multiplication of σ by the cube root of nucleus mass, and of τ by the nucleus mass raised to the $\frac{2}{3}$ power, converts coordinates to droplet radius in microns and time in seconds.

from (16) and (17) justifies the use of the simplified form, (17), in subsequent calculations.

3. Measurement of growth rates

To test the validity of the derived growth equations, it was necessary to observe the size of a growing sea-salt particle as a function of time under known conditions. The principal condition was that the relative humidity be changed nearly discontinuously from a value below 78 per cent, where the nucleus is essentially dry crystal, to a constant measurable value above 78 per cent, which will cause growth. Also, it was necessary that a constant temperature and air flow be maintained during growth.

Apparatus.—A schematic diagram of an apparatus which fulfilled these conditions is presented in fig. 3. The principal components were: (a) a system to provide a continuous flow of air of constant humidity; (b) measuring units consisting of a flowmeter and psychrometer; and (c) a microscope and special stage to permit observation of the growing particle.

(a) Basically, the humidity system was of the divided-flow type outlined by Wexler and Brombacher (1951). The desired humidity was obtained by recombination of a divided air stream, one portion of which was saturated by bubbling through a heated column of water, and the other desiccated by passage through silica gel. The humidity was controlled by adjustment of the relative flow in the two branches, by means of a needle valve in the dry branch.

(b) After passing through the generating system, the air stream normally flowed through a proportioning valve and a capillary flowmeter, which served to control and measure the flow. Calibration of the flowmeter by the usual displacement method gave an average deviation of 0.3 per cent for rates of flow between 2 and 18 cm³/sec. At high relative humidities,

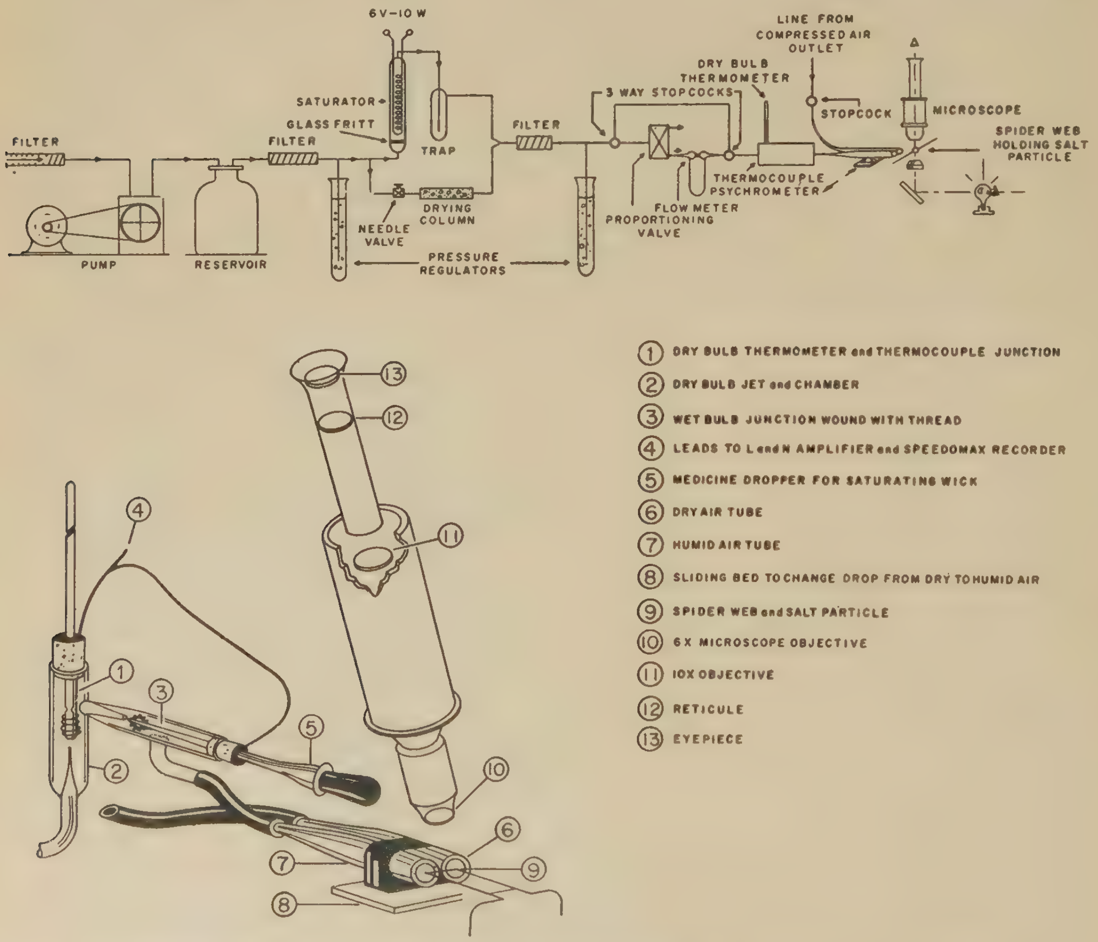
6V–10 W
SATURATOR
GLASS FRITT
FILTER
FILTER
TRAP
FILTER
DRYING COLUMN
NEEDLE VALVE
PUMP
RESERVOIR
PRESSURE REGULATORS
LINE FROM COMPRESSED AIR OUTLET
DRY BULB THERMOMETER
3 WAY STOPCOCKS
STOPCOCK
MICROSCOPE
SPIDER WEB HOLDING SALT PARTICLE
THERMOCOUPLE PSYCHROMETER
FLOW METER
PROPORTIONING VALVE
① DRY BULB THERMOMETER and THERMOCOUPLE JUNCTION
② DRY BULB JET and CHAMBER
③ WET BULB JUNCTION WOUND WITH THREAD
④ LEADS TO L and N AMPLIFIER and SPEEDOMAX RECORDER
⑤ MEDICINE DROPPER FOR SATURATING WICK
⑥ DRY AIR TUBE
⑦ HUMID AIR TUBE
⑧ SLIDING BED TO CHANGE DROP FROM DRY TO HUMID AIR
⑨ SPIDER WEB and SALT PARTICLE
⑩ 6 X MICROSCOPE OBJECTIVE
⑪ 10X OBJECTIVE
⑫ RETICULE
⑬ EYEPIECE
①
②
③
④
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FIG. 3. Schematic diagram of growth-rate apparatus, including detailed drawing of psychrometer and microscope.

the pressure drop across these units prohibited their use; therefore, a bypass was provided.

The next unit, the psychrometer, is shown in the detail drawing in fig. 3. This unit, which with the rest of the apparatus was constructed mainly of glass tubing for the purposes of cleanliness and low heat conduction, was further protected against random heating by a thick layer of insulation. The copper-constantan thermocouple was similar to those described by Powell (1936). The thermocouple leads were connected to a Leeds and Northrup D.C. amplifier and *Speedomax* recorder (not shown in fig. 3). The psychrometer was calibrated by a gravimetric determination of the vapor absorbed from a known volume of air. Humidities measured by the psychrometer were found to be within 0.5 per cent of those calculated by the gravimetric method.

(c) Fig. 3 also includes a detail drawing of the microscope and the humidity switching mechanism mounted on the stage. The double objective lens-system was necessary, to allow a magnification of 625 diameters with a 1-cm working distance. The switching mechanism consisted essentially of two tubes (one connected to the humid air supply, the other to a compressed air outlet) on a sliding bed. The particle under observation, which was mounted on a spider web in close proximity to the mouth of the tubes, could thus be bathed either by air of a known high humidity or by dry air of 30 to 40 per cent relative humidity. The particles were obtained by passing the web through a mist of sea water. Dessans' (1947) procedure was employed for obtaining and mounting spider webs.[4]

The time measurement was performed by means of the scale-marking pen of the Speedomax recorder. A chart speed of 1 in/min permitted time estimation to the nearest second.

Experimental procedure.—The derived growth equations predict that the rate of growth should be dependent upon three variables, mass of salt, humidity and temperature. A fourth possible variable is the rate of air flow past the growing particle, which was ignored in the development of the growth equation. The design of the apparatus permitted the control of three of these, but since room air of fairly constant temperature was pumped through the apparatus, no attempt was made to investigate the temperature dependence. The effect of each variable was investigated independently, by keeping the others nearly constant during a series of measurements. Repeated runs were made at low humidities, to obtain a sufficient number of diameter measurements.

After the apparatus had become stabilized so that no humidity variations greater than 0.5 per cent occurred within periods of a half-hour, the flow, dry-bulb temperature, and initial diameter of the

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[4] Woodcock (1952) reports some preliminary growth rates, measured in a chamber which was flushed with moist air. The overly long growth times he obtained were probably caused by the inability to obtain a discontinuous humidity change by such flushing methods.

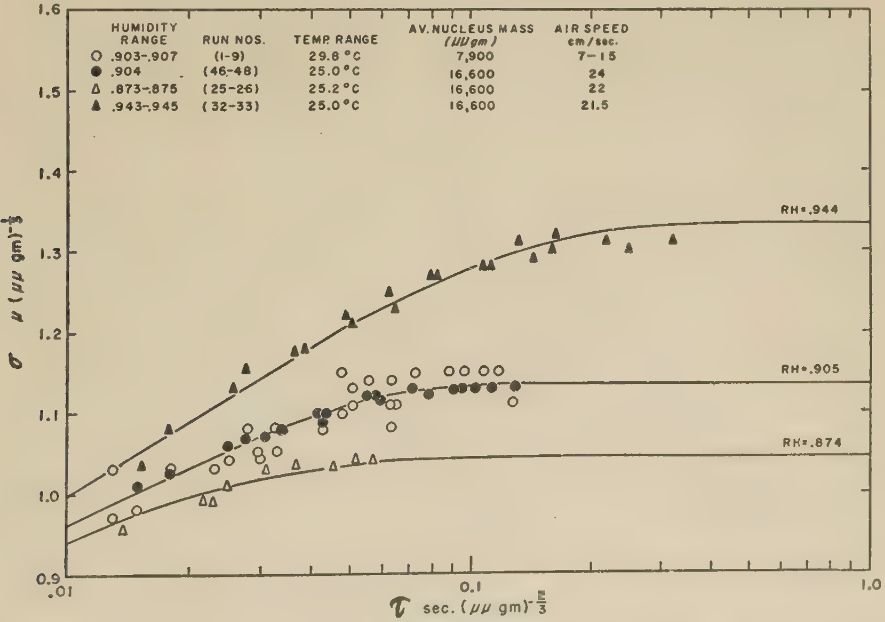

FIG. 4. Comparison of experimental data with growth curves interpolated from fig. 2. Legends following each symbol relate humidity range, sequence numbers of runs, dry-bulb temperature range, average nucleus mass, and air speed during measurement.

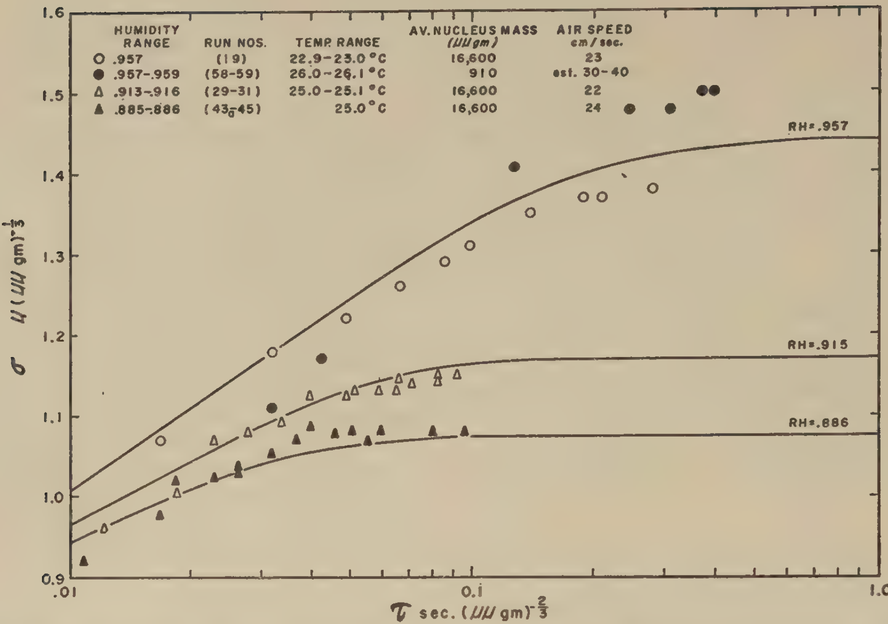

FIG. 5. Comparison of experimental data with growth curves interpolated from fig. 2. Legends following each symbol relate humidity range, sequence numbers of runs, dry-bulb temperature range, average nucleus mass, and air speed during measurement.

particle were recorded. Following the humidity shift, the diameter of the growing drop was recorded until no further change was observed. Time marks were made simultaneously, the initial mark indicating the humidity shift, and succeeding marks corresponding to diameter readings. The temperature and flow were recorded at intervals during the run. The humidity and flow were obtained, respectively, from the psychrom-

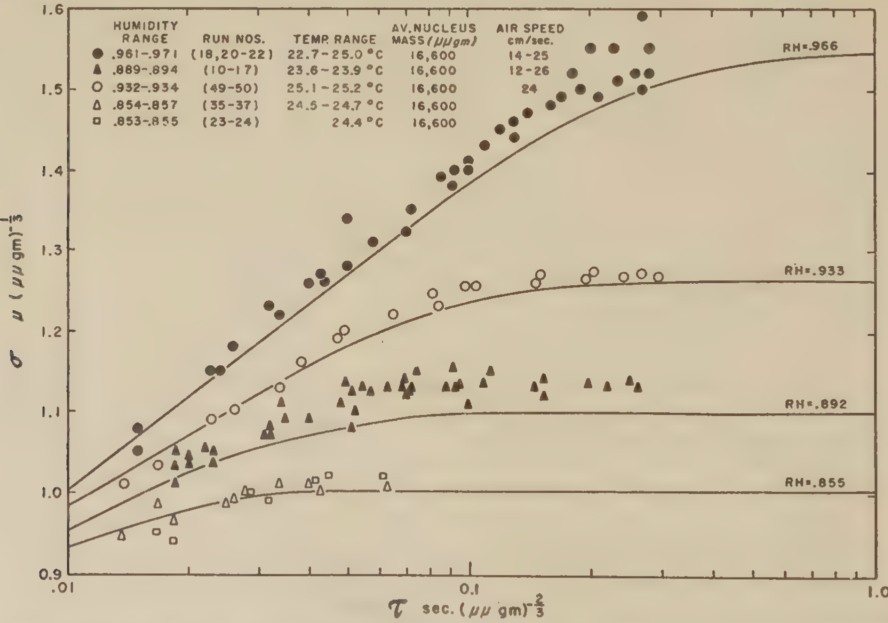

FIG. 6. Comparison of experimental data with growth curves interpolated from fig. 2. Legends following each symbol relate humidity range, sequence numbers of runs, dry-bulb temperature range, average nucleus mass, and air speed during measurement.

etric chart and calibration curve, and the mass of salt was calculated from the equilibrium diameter and humidity by the isopiestic method outlined by Woodcock (1949).

After completion of a series of runs on a given salt particle, the data were averaged to obtain the best possible experimental value of mass of the particle, and this mean was used to scale the diameter and time measurements in accordance with (11) and (12).

4. Comparison of experimental results

The experimental results are plotted in figs. 4 through 7. A logarithmic time scale is used in these figures, to spread out scaled time values in the early stages of growth.

Runs 1–9, represented by the open circles of fig. 4, were made with a 7900-$\mu\mu g$ particle at rates of air flow between 7 and 15 cm/sec. Similarly, runs 10–17 were performed with a 16,600-$\mu\mu g$ particle at flows between 12 and 26 cm/sec. The same 16,600-$\mu\mu g$ salt particle was used for runs 18 through 53. The final series of runs, numbers 54 through 60, were performed with a considerably smaller 910-$\mu\mu g$ particle.

The theoretical curves of figs. 4–7 were obtained by graphical interpolation between those of fig. 2.

Before discussion of the comparison between experiment and theory, it is necessary to estimate the effects of observational errors upon the data. The scatter of the individual diameter measurements was caused by the difficulty in estimation of the changing diameter of the droplet at a given instant of time. The diameters were read on a reticule with a calibration of 2.4μ per scale unit. Thus, if either edge is estimated to ± 0.2 of a scale unit, the diameter is good to $\pm 1\mu$ which amounts to $\pm 0.04\sigma$ units for the largest particle observed ($16{,}600\mu\mu g$). For a 1000-$\mu\mu g$ particle, the error of an individual diameter measurement increases to $\pm 0.1\mu\ (\mu\mu g)^{-\frac{1}{3}}$.

The psychrometer introduces another significant source of error. The calibration indicates that the precision of a humidity measurement is ± 0.5 per cent. The effect of this may be estimated directly from fig. 2, by interpolation between the growth curves. Errors in σ of 2 to 6 per cent are possible, depending upon the humidity and stage of growth. It should be noted in fig. 7 that the data tend to fall near the saturation curve, although the measured humidity is from 1 to 2 per cent less than saturation. These deviations are not surprising, since random heating, slight pressure drops, and condensation on the tubing walls make the attainment and maintenance of these high humidities difficult.

In view of the possible errors, it is apparent that the agreement between experiment and theory is

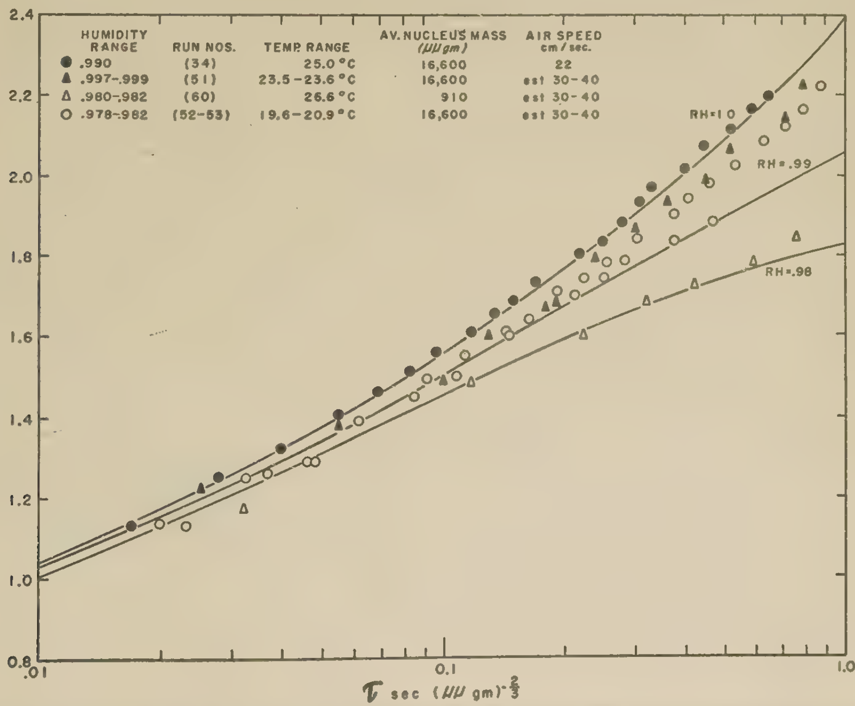

Fig. 7. Comparison of experimental data with growth curves interpolated from fig. 2. Legends following each symbol relate humidity range, sequence numbers of runs, dry-bulb temperature range, average nucleus mass, and air speed during measurement.

generally good. All the deviations from the computed curves are within, and usually considerably less than, the estimated limit of experimental error. Therefore, it is concluded that the approximate growth equation (17) satisfactorily describes the growth of saline particles in a humid atmosphere. The mathematical approximations, neglect of heat storage effects, and use of macroscopic diffusion and heat-conduction coefficients are valid. However, the 3 to 14 per cent difference between the equilibrium scaled radii of (18) and those computed by Wright's (1936) formula indicate that the use of a Raoult's law vapor-pressure dependence in earlier work led to significant error.

The effect of ventilation was investigated in two series, runs 1–9 and 10–17. In both series, separate runs were made with the same particle and humidity, but with different rates of flow. There is no observable variation in growth rate over the range of flows measured (7 to 26 cm/sec). Below the velocity of 7 cm/sec, there were indications of a slower rate of growth. However, it is believed that this was due principally to the increased time necessary for changing the droplet surroundings.

When the bypass of the flowmeter was used for runs at high humidities, the velocity of air flow was estimated to be between 30 and 40 cm/sec. No velocity effect was apparent in the comparison between the data from these runs and the theoretical curves.

The observed absence of a ventilation effect agrees with the results obtained by Kinzer and Gunn (1951). They found that the rate of evaporation of drops falling at terminal velocities less than 0.5 m/sec was also predicted by a static diffusion equation.

5. Growth under variable humidity conditions

Now that the formulations derived in section 2, above, have been shown to be valid, it is of interest to apply them to problems of meteorological significance. The essential agreement between the foregoing development and those of Howell (1949) and Squires (1952), and the excellent treatments given by these writers for conditions prevailing within a cloud, preclude any great improvement by rediscussion of that phase of the problem. However, an estimate of the size of droplets in sub-cloud air would be of use in understanding the role of salt nuclei in rain formation and visibility.

As an illustration of the use of the growth equation (17), the equation was applied to the arbitrary situation of a particle rising at a steady rate from an atmosphere approximating that near the sea surface in the trade-wind areas ($T_1=25C$, $H=0.65$). It is

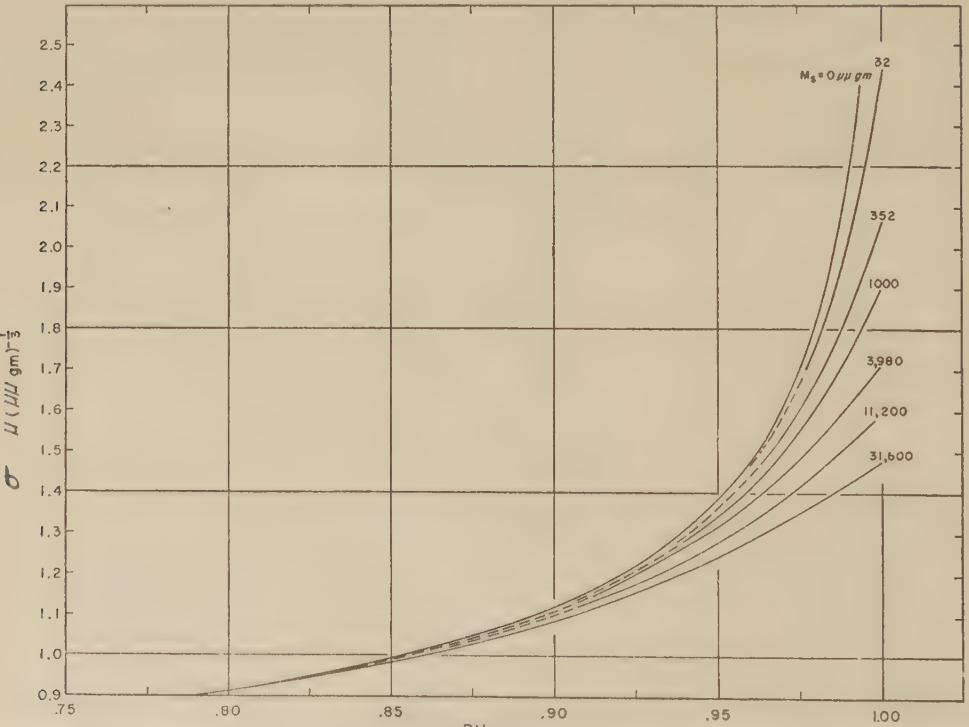

FIG. 8. Variation of σ with humidity for particles of indicated nucleus masses rising at 1 m/sec from level of 25C and 65 per cent relative humidity. Temperature decrease is assumed to be 1C/100 m.

also assumed that the temperature falls 1C/100m, corresponding to a dry-adiabatic expansion. Since the growth equation is primarily humidity dependent, and only slightly temperature dependent, the initial temperature and humidity conditions are not critical, save in that the humidity be less than the solution point, $H=0.78$. The use of a dry-adiabatic lapse rate makes the rate of rise nearly proportional to the time rate of change of humidity, which is the parameter utilized in (17).

By use of the specified conditions, (17) becomes

$$\sigma\frac{d\sigma}{dH}=\frac{2\times10^3A}{Vm_s^{\frac{1}{3}}}\ln\frac{1-0.146\,\sigma^{-3.35}}{H}. \qquad (21)$$

After choice of a suitable updraft (1 m/sec) and nucleus size, (21) was numerically integrated to yield growth curves. The results of these integrations are presented in fig. 8. Curves at other updrafts were obtained by a simple shift of variables in (21). Identical growth curves will be obtained for two different particles rising at different rates, if $Vm_s^{\frac{1}{3}}$ is the same in both cases.

Fig. 9 shows the droplet size attained by particles of the indicated masses at the saturation level (cloud base), following a steady rise at the indicated rate. It is apparent that the rate of rise does not greatly affect the droplet size attained by the more numerous small particles. Consequently, it is to be expected that most of the 1-m/sec curves of figs. 8 and 9 would apply under normal atmospheric conditions, even with erratic updrafts and variable initial conditions.

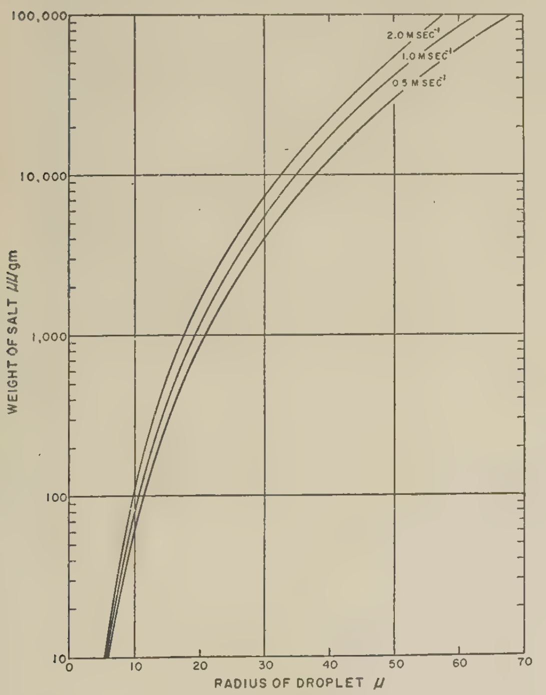

Fig. 9. Calculated radius of sea-salt droplets at cloud base (H = 1.0) as function of nucleus mass and rate of rise. Initial conditions are same as those of preceding figure.

The apparent growth of all particles of mass less than 50 $\mu\mu$g to a radius of about 5μ coincides with Howell's findings that very small nuclei generate a narrow spectrum of droplet sizes. This is presumed to be caused by rapid growth of these particles to an extremely dilute droplet, the growth of which is thenceforth almost independent of the mass of the original nucleus.

In Fig. 9, a radius of 15μ or more is attained by particles of mass greater than 400 $\mu\mu$g, which are present in trade-wind regions in numbers comparable to raindrops (500–5000 per cubic meter, Woodcock, 1952). These particles are of sufficient size to grow at an appreciable rate by accretion of smaller droplets. The accretional rate of growth, as estimated by Houghton's (1950) curve, is approximately a tenth to a hundredth of the condensational rate for nuclei of the sizes indicated by fig. 9. However, the accretional rate rapidly increases, while the condensational rate decreases, with increasing droplet size. This would make it probable that condensational growth within the cloud layer is of secondary importance to the process of accretional growth in the formation of raindrops upon salt nuclei.

Acknowledgment.—The writers are indebted to Mr. Alfred Woodcock for his helpful advice on the experimental portions of this work, and for the original impetus to undertake this study. They also wish to thank Mrs. Mary C. Thayer, who performed the computations upon the original data.

APPENDIX

List of symbols

q = quantity of water vapor (g)
Q = quantity of heat (cal)
$d\rho/dR'$ = vapor-density gradient (g/cm^4)
dT/dR' = temperature gradient (K/cm)
R' = radial distance (cm)
D = diffusion coefficient of water vapor in air (cm^2/sec)
k = heat-conduction coefficient of moist air (cal cm^{-1} sec^{-1} deg^{-1})
c_p = specific heat of water at constant pressure (cal g^{-1} deg^{-1})
T_1 = temperature of surrounding air (deg)
T = temperature of droplet (deg)
ρ_1 = vapor density of surrounding air (g/cm^3)
ρ = vapor density of droplet at temperature of droplet (g/cm^3)
P_1 = vapor pressure of surrounding air (mm Hg)

P = vapor pressure of droplet at temperature of droplet (mm Hg)

P_2 = vapor pressure of droplet at temperature of surrounding air (mm Hg)

t = time (seconds)

m = mass of droplet (g)

m_s = mass of salt particle (g)

m_w = mass of water in droplet (g)

r = radius of droplet (cm)

r_1 = initial radius of droplet (cm)

ρ_s = density of solution comprising droplet (g/cm^3)

L = latent heat of condensation of water vapor (cal/g)

R = gas constant [cal mole^{-1} deg^{-1} or. cm^3 (mm Hg) mole^{-1} deg^{-1}]

M = mole weight of water (g/mole)

σ = scaled radius [cm/g$^{\frac{1}{3}}$ or $\mu/(\mu\mu g)^{\frac{1}{3}}$]

τ = scaled time [sec/g$^{\frac{2}{3}}$ or sec/$(\mu\mu g)^{\frac{2}{3}}$]

ΔP = vapor-pressure lowering (mm Hg)

H = fractional relative humidity

P_0 = saturation vapor-pressure (mm Hg)

σ_{eq} = equilibrium scaled radius

τ_0 = scaled time for growth from dry crystalline mass to droplet of saturated solution

V = rate of rise of particle (m/sec)

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SOME RESULTS OF A TRADE-CUMULUS CLOUD INVESTIGATION

By Joanne Starr Malkus

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ABSTRACT

Cross sections through two trade-cumulus clouds are presented, showing the temperatures, turbulence, and water-vapor content of the clouds and their nearby environment, the cloud slope, and the external wind profile. The two clouds were studied over the Caribbean Sea on the same afternoon in June, 1952, and were in widely differing phases of their life cycles. The measurements were made from a slow-flying aircraft, equipped with sensing instruments and whose behavior as a meteorological tool had been previously studied. Numerous calculations are made from the cross sections, including total and dynamic entrainment, drafts, slopes, and liquid-water content. These are, where possible, checked against the corresponding observations. In addition to testing previously evolved theoretical models, and the usefulness of the steady-state hypothesis, the data provide some evidence concerning the formation and growth of larger trade-cumulus clouds from several smaller ones and by successive stages.

1. Introduction

The important role of trade-cumulus clouds in the budgets of the low-latitude atmosphere and in the energy supply for the global wind systems has been established. These marine clouds are, furthermore, examples of the convective process operating under more uniform and relatively less complex conditions than in the case of land cumulus in middle latitudes. Finally, trade cumuli are the major cloud forms which commonly produce precipitation at above freezing temperatures. Although the present study is not directly concerned with condensation and precipitation processes, it is contended that without the introduction of information concerning the draft structure and dynamics of the clouds, the growth of theories in the field of "cloud physics" and precipitation must be drastically hampered.

Important advances in trade-cumulus dynamics began with the Wyman-Woodcock Caribbean expedition in 1946. Their results revealed several important features of these clouds, among them: (1) the cumuli appeared not to possess "roots," or cloud-scale drafts extending well below individual cloud bases, and (2) a significant amount of mixing (entrainment) between cloud and environment was inferred from comparison between cloud and clear-air temperature and moisture soundings (Stommel, 1947).

Since that time, considerable work has been done on a steady-state model of trade cumuli, based on ideas of entrainment. Relative horizontal cloud-air motions have been studied, and the dependence of cumulus slopes on cloud and environment parameters has been predicted. So far, a time-dependent, or life cycle, cumulus model has not been evolved. Prior to such an attempt, it has been considered necessary to answer certain questions by further observations. In addition to the checking of the Wyman-Woodcock results and of the foregoing cited theoretical work, it was necessary to investigate carefully the resistance forces operating against cumulus growth. It was desired to determine whether a functional dependence of entrainment upon cloud and environment parameters could be established, and whether or not additional resistances due to "form drag" or pressure forces must be taken into account.

To answer these questions, nearly simultaneous cross-sections at several levels through a cloud and nearby environment were desired. These should include measurement of drafts, turbulence, temperature, water-vapor and liquid-water content, cloud slope and environmental wind shear. To obtain such observations, a PBY-6A aircraft was secured by the Woods Hole Oceanographic Institution, on loan through the Office of Naval Research and the Bureau of Aeronautics, U. S. Navy. The extensive studies of this airplane as a meteorological tool, and the details of its instrumentation, will be discussed in other reports

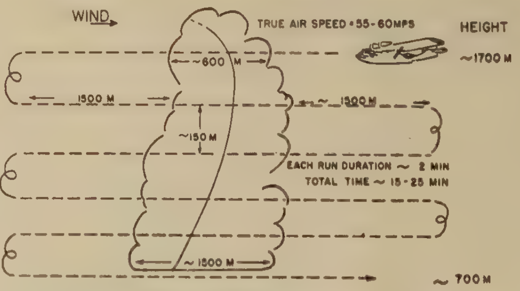

FIG. 1. Schematic diagram illustrating manner in which cumulus clouds were traversed by PBY. One earlier run was made (usually flying downwind) past cloud at distance from it of 4–5 mi, so that cloud could be photographed in plane of wind. Topmost run was made at same level at which photograph was taken.

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[1] Contribution No. 667 from the Woods Hole Oceanographic Institution.

from the Woods Hole Oceanographic Institution. The present paper is confined largely to a discussion of some of the results of measurement, and the calculations therefrom. The consistency of these, or lack thereof, will provide an indication of the adequacy of the instrumentation.

2. Methods of measurement and observational procedures

The clouds were investigated by the airplane in the manner shown in fig. 1. Prior to entering the selected cloud at the topmost level, the aircraft passed the cloud tower (flying downwind) at a distance of several miles to obtain one or two still photographs of its slope in the plane of the wind. The cloud was always first entered at the same altitude at which the photograph was taken. This information, in addition to knowledge of the height of the cloud base, permitted accurate reconstruction of the cross section by combination of the airplane records and the photographs. The airplane was ordinarily flown at an airspeed of about 50–60 m/sec. The traverses of a single cloud, consisting of five to seven horizontal runs, could be completed in a time interval of 15–25 min. Prior to the field work, it was doubted whether any cloud would remain in even a quasi-steady state for this length of time, and therefore whether calculations based upon the steady-state models would be meaningful. The present paper should indicate where and to what degree these doubts are justified.

During the June 1952 field work in the vicinity of San Juan, Puerto Rico, several clouds were examined in which all the desired measurements, except that of liquid water, were obtained to varying degrees of accuracy. The temperatures and water vapor contents were obtained from records by a modified form of the Massachusetts Institute of Technology psychrograph, the performance and accuracy of which are discussed elsewhere (McCasland, 1951). It is pertinent to note that, since the response time of this instrument is approximately 2 sec, the records of dry- and wet-bulb temperatures, virtual temperatures, and mixing ratios represent averages over roughly 100-m horizontal distances. The turbulence is described by a parameter called "turbulence index," introduced earlier by

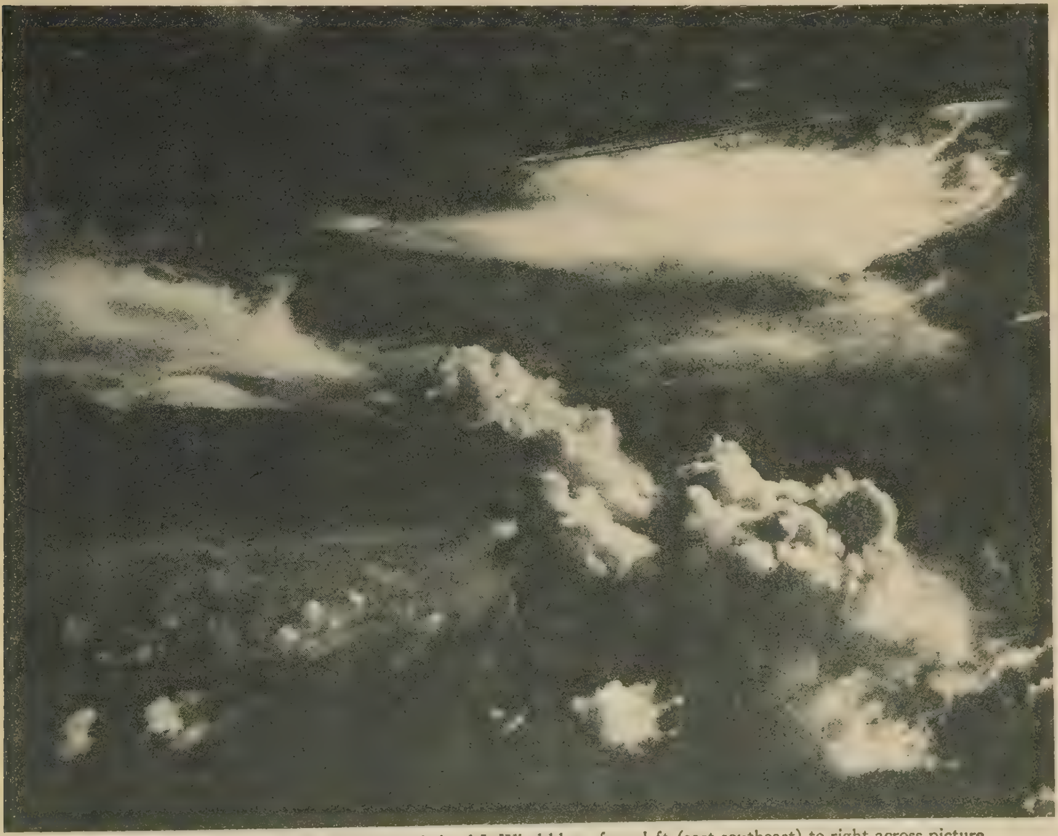

FIG. 2. Photograph, in plane of the wind, of cloud I. Wind blows from left (east-southeast) to right across picture.

Malkus and Bunker (1952). It is determined from the records of a water-column accelerometer[2] by planimetering the envelope of the trace over distance intervals of about 240 m. It thus gives the relative development of small-scale roughness within these intervals. External wind profiles were obtained by double drift of the aircraft, and although drifts were determined independently by two sights and observers, these results are probably less accurate than single-theodolite pilot-balloon observations, especially when whitecaps were absent from the sea surface.

The most crucial measurements were of drafts. These were obtained by integration of the records of the water-column accelerometer. Studies of the flight characteristics of the aircraft, leading to justification of this method, are reported on by Brewer (1954). It was attempted to fly the airplane at constant attitude and airspeed in the cloud runs, and if this assumption is met, the vertical motions of the air are given by the following equation:

$$w = \sum \bar{a}\,\Delta t + \frac{1.25\,\bar{a}M}{\frac{1}{2}\rho S V(dC_L/d\alpha)}, \qquad (1)$$

where $\bar{a}$ is the average observed vertical acceleration of the airplane during the time interval Δt, the summation sign indicates an algebraic summing process begun at the commencement of the run, M is the plane's mass, ρ the air density, S the wing area, V the airspeed, and $dC_L/d\alpha$ is the variation in lift coefficient with angle of attack, known for this airplane. The first term on the right gives the average vertical velocity of the aircraft relative to the ground during Δt, while the second term gives the sinking speed of the plane through the air. This equation, and its derivation and use, are discussed in more detail by Bunker (1953).

Recent modification of the PBY instrumentation will permit corrections for deviations from constant airspeed and attitude, not feasible in the 1952 field work. Subsequent tests (March 1953) in which these departures were measured in trade cumuli show that, when $\frac{1}{2}$-sec averages (approximately 25 m in horizontal distance) are taken from the records, errors due to these combined effects may equal or occasionally exceed ±50 cm/sec, the larger contribution usually originating in attitude departures. When, however, an average over an entire draft (approximately 200–300 m distance) is taken, the records showed that the omitted combined correction did not exceed ±10–15 cm/sec. Therefore, in the 1952 cloud records, only average draft speeds may be expected to be of sufficient accuracy to be compared with theoretical calculations. Nevertheless, in a small fraction of the clouds pene-

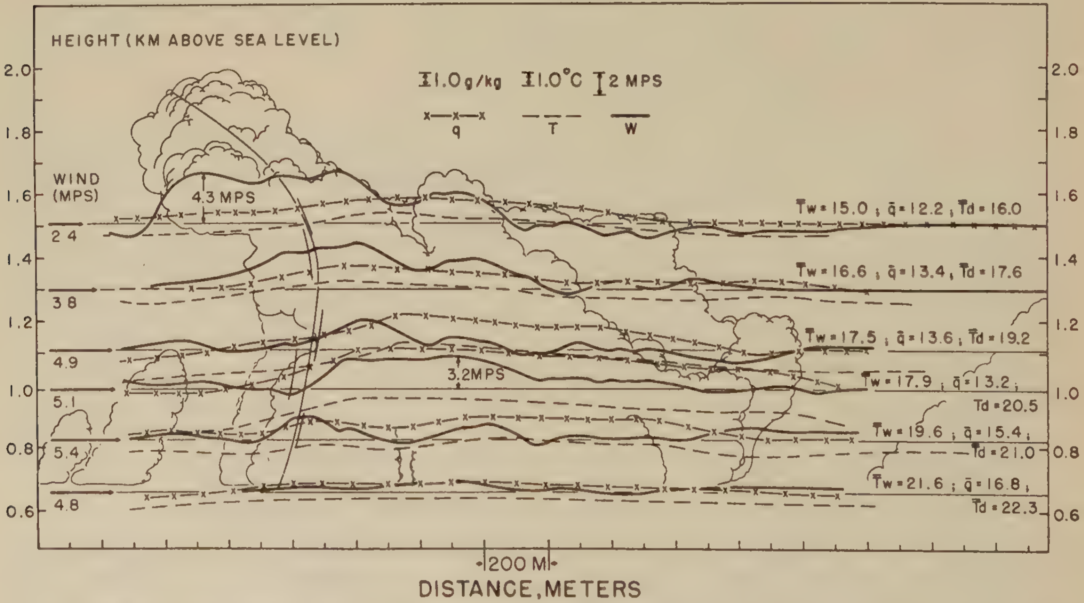

FIG. 3. Summary of data taken for cloud I, put together with aid of fig. 2. Solid curves are vertical draft velocities (running mean values over 150-m distance), with origin being thin horizontal line at each level. Dashed lines are temperatures, assuming saturation within cloud boundaries, so that inside cloud the wet-bulb temperatures are used; dry-bulb temperatures are represented outside. x-ed lines are mixing ratios. Figures to far right are environment wet-bulb temperature, mixing ratio, and dry-bulb temperature, respectively. Latter two are taken as values of origins of x-ed and dashed curves. Calculated (see table 4) slope of cloud is given by heavy curved line. Winds obtained by double drift of aircraft are shown by arrows at the extreme left. Note separation of larger drafts into smaller ones at 830-m level, where one of the large vertical holes in cloud is indicated.

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[2] "Accelerometer for air turbulence measurements," by Allyn C. Vine. Memorandum on file at the Woods Hole Oceanographic Institution, August 1945.

trated, it was believed by the observers that, due to the relative isolation of the clouds or other factors leading to unusually accurate flying, the smaller-scale draft structure ($\frac{1}{2}$- and 3-sec averages) might be meaningfully obtained by application of (1).

Two such clouds were encountered on 28 June 1952, near St. Croix, Virgin Islands. On this day, all instruments were working well, and fairly isolated clouds persisted under apparently steady conditions during seven or more horizontal passes by the airplace. The two clouds studied possessed upper portions, or towers, in widely differing phases of their life cycles. One was in the very active phase, perhaps still growing, in which no significant downdrafts were present; the other tower, although not apparently evaporating, was in a more mature phase with strong downdrafts present near its top. This and other aspects of the two clouds form a very interesting contrast.

3. Theoretical model used and calculations to be made

Numerous sets of observations of the kind described by fig. 1 indicated a typical relation between a cloud, defined visually by the presence of liquid droplets, and the updrafts which compose it. These observations showed that, at a single horizontal traverse, a middle-sized trade cumulus usually contained from one to three updrafts of diameter ranging from 200–1500 m and mean ascent speeds from 1–7 m/sec. Although these drafts were not square in profile, they approximated this shape sufficiently so that it was considered meaningful to define the draft boundaries by the locations of measured zero vertical ascent, and to take an average rate of rise between these boundaries to use in comparison with the theoretical calculations. Downdrafts, of similar scale, were treated in the same manner on those occasions when they appeared near the cloud top.

The data further showed that a single draft, so defined, could readily be traced on the records from one level to the next, often throughout the vertical extent of a cloud. The analysis presented here will usually concern the major updraft in a given cloud, traced upward from near the cloud base to the highest level traversed. On many occasions, two smaller-diameter drafts near the cloud base appear to join at a higher level to form a single rising column. In such cases, the two drafts are combined into one for the calculation.

The theoretical model is that evolved originally by Stommel (1947; 1951) and extended by Malkus (1949; 1952b) and others. A steady-state ascending column of air is considered, which is homogeneous and discontinuously distinct from its environment. It is continually exchanging air with the surroundings by entrainment and efflux, and its cross section, assumed circular, may change magnitude in an arbitrary manner with height. With the foregoing assumptions, mass- and

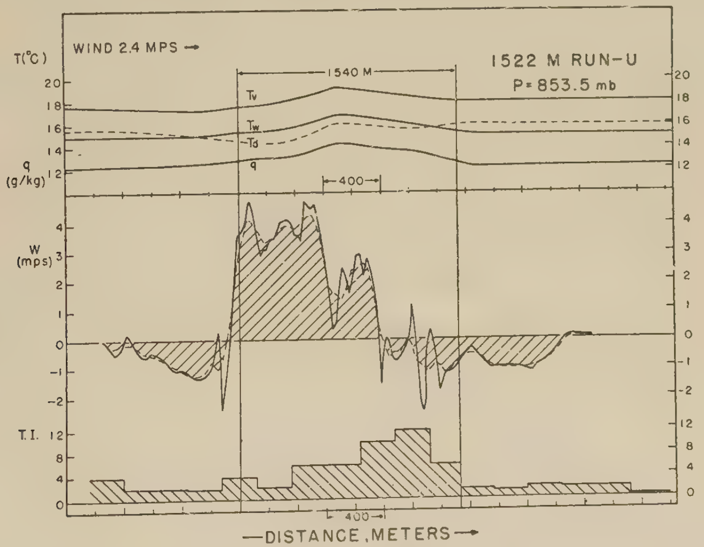

Fig. 4. 1522-m run through cloud I. *U* designates fact that it was flown in upwind direction (right to left). Solid vertical lines 1540 m apart, designate that part of record actually within liquid cloud. T_v stands for virtual temperature, T_w for wet-bulb temperature, T for dry-bulb temperature, q for mixing ratio. Curves marked w are vertical velocities, solid curve being composed of values found from integrating accelerations read off every 25 m, dashed (shaded) curve being running averages of six of these values, or 150-m averages. Bottom curve, *T.I.*, is turbulence index, and numerical values are of significance only relative to each other. Note that shortly after entry into cloud, dry-bulb temperature becomes lower than that of wet-bulb. This results from wetted dry-bulb, upon readings of which dry dynamic correction is still applied. Within cloud, dry- and wet-bulb temperatures were assumed equal, and wet-bulb curve was used to obtain mixing ratio and virtual temperature. Also note single smooth peak of temperature and mixing ratio within cloud, and flatness of these curves outside cloud boundaries.

momentum-continuity formulae may be set up and their results compared to the observations, the comparison constituting a test of the model used.

First, based on the method of Stommel (1947), it is possible to calculate the total amount of outside air mixed into the draft from one level to the next, called "gross entrainment" by Malkus (1952a). This is done from the psychrograph records, by a comparison of mean temperatures and moisture contents of drafts and nearby environment. Second, the net or "dynamic entrainment" (see Houghton and Cramer, 1951) may be computed from the vertical-velocity records. The mass flux, M, through any level within the draft is given by

$$M = A\rho w_d, \tag{2}$$

where A is the cross-sectional area of the draft, ρ the air density within the draft, and w_d is its mean vertical velocity at that level. Thus,

$$dM/dz = \rho\, d(Aw_d)/dz,$$

where $d\rho/dz$ is several orders of magnitude less than the other terms, and

$$\frac{1}{M}\frac{dM}{dz} \equiv \text{dynamic entrainment} = \frac{1}{Aw_d}\frac{dAw_d}{dz}. \tag{3}$$

The data give $A(z)$ and $w(z)$, as discussed before. Between two levels, $(1/M)\, dM/dz$ may be compared with $(1/M)\, dM_i/dz$, the gross entrainment computed by Stommel's method. For internal consistency, the latter quantity must be equal to or greater than the former. In the case that the gross entrainment is greater, a quantity of air per second, dM_0, has left the updraft during transit from the lower level z to the upper, $z + dz$, giving a proportional rate of efflux $(1/M)\, dM_0/dz$.

We may now further write a continuity equation for vertical momentum in the entraining updraft between z and $z + dz$, namely

$$d(Mw_d) = w_E\, dM_i - w_d\, dM_0 + \alpha A \rho\, dz + \sum F, \tag{4}$$

where w_E is the mean vertical velocity of the air entrained; the term $\alpha A \rho\, dz$ is the change in momentum created by buoyancy forces, and the term $\sum F$ is the sum of all the other forces, such as form or pressure drag and the weight of droplets. This last term will henceforth be treated as negligible, and one of the major purposes of this paper is to learn the degree to which this assumption is justifiable. In the buoyancy term, α, the buoyancy acceleration is defined as

$$\alpha = g(T_v - T_v')/T_v',$$

where T_v is the mean virtual absolute temperature within the draft, T_v' the corresponding value for the environment, and g is the acceleration of gravity.

The hypothesis will be tested here that any momentum flux increase with height is generated by the buoyancy force, or that (4) may be written as

$$d(Mw_d) \approx \alpha A \rho\, dz, \tag{5}$$

which, for calculation purposes, becomes

$$\frac{\bar{\alpha}}{w_{d0}^2} = \frac{1}{\bar{A}}\frac{\Delta A}{z_1 - z_0} + \frac{2}{w_{d0}}\frac{\Delta w_d}{z_1 - z_0}, \tag{6}$$

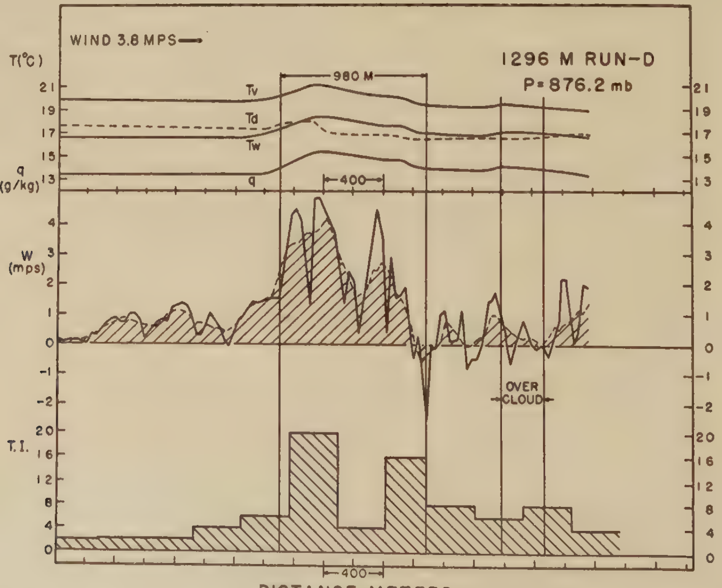

FIG. 5. 1296-m run through cloud I. Notation same as in fig. 4, except that D stands for fact that run was flown in downwind direction (left to right). Note that another, smaller cloud tower was passed over, indicated by shorter pair of vertical lines.

when (2) is introduced. Here the bars indicate the mean of the observations at z_0 and z_1, and the stepwise integration is started by taking the observed w_{d0} at the lowest level of the cloud investigated.

Use of (5) and (6) implies, from comparison with (4), that

$$w_E\, dM_i - w_d\, dM_0 \approx 0,$$

or

$$w_E \frac{1}{M}\frac{dM_i}{dz} \approx w_d \frac{1}{M}\frac{dM_0}{dz}, \tag{7}$$

or that a negligible amount of momentum is exchanged between draft and surroundings, the changes in the draft being created by buoyancy therein. To avoid misunderstanding, it must be emphasized that (6) and (7) do not imply that the effects of entrainment upon the draft are small, since the buoyancy acceleration at each level will be critically affected by the amount of outside air mixed into the draft.

The predictions of (6) may be tested in two ways, the first being comparison of the calculated $w(z)$ with that observed. A second, rougher check consists of separate application of (7), finding $(1/M)\, dM_0/dz$ by subtracting the dynamic from the total entrainment, calculating w_E, and determining whether the result is consistent with the data. The latter check is only very approximate, since it will be seen that there is considerable uncertainty in specifying the vertical motion, w_E, of the entrained air.

In those cases where one or both of these checks gives unsatisfactory results, an attempt will be made to apply a more general form of (4), namely

$$\frac{1}{w_{d0} - w_E}\frac{dw_d}{dz} = -\frac{1}{M}\frac{dM_i}{dz} + \frac{\bar{\alpha}}{w_{d0}(w_{d0} - w_E)}, \tag{8}$$

where only $\sum F$ has been omitted from (4), and the definitional relation $dM = dM_i - dM_0$ has been used. This equation, although it does not require the assumption that negligible momentum is exchanged between draft and environment, is less suitably used with the present data than (6), since an assumption or knowledge concerning w_E is required. Thus, it will be called upon only when (6) proves unsatisfactory. Finally, in the case of the totally unmixed and non-interacting parcel, (4) leads to

$$dw_p/dz = \alpha/w_p. \tag{9}$$

The vertical velocity, w_p, of the non-interacting parcel, rising moist adiabatically from the cloud-base level, will also be calculated, for comparison with observed drafts and the results of the entrainment model.

While a comparison of measured draft profiles with the results of calculations from (6) and (8) should yield some idea of whether significant amounts of "form drag" are resisting the vertical growth of the cumuli, the cloud slope may be calculated to enquire about horizontal resistance forces. This method has been described in detail by Malkus (1952b). When the steady-state assumption is permissible, the slope of an updraft at any level is simply the ratio of its vertical speed to the difference in its horizontal speed between that level and draft base, namely

$$\tan\theta \equiv \text{slope} = w_d/(u_d - u_{0E}), \tag{10}$$

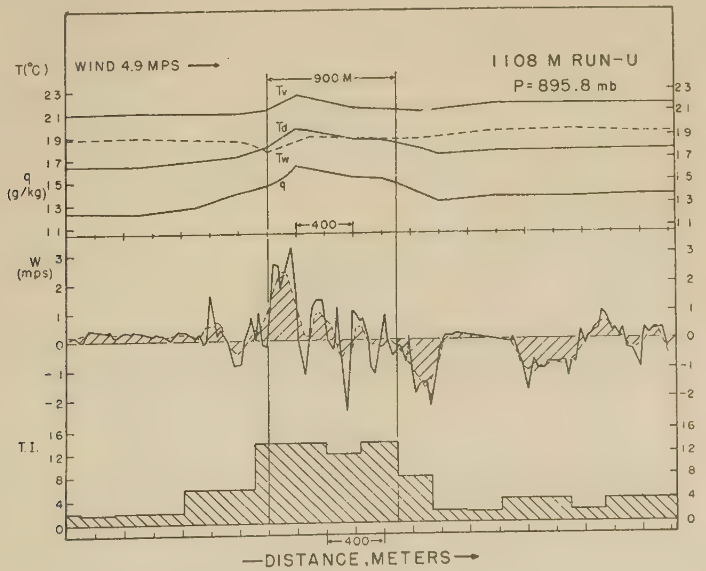

FIG. 6. 1108-m run through cloud I. Notation same as in fig. 4.

where u_d is the horizontal velocity of the draft air in the plane in which the slope is desired, and u_{0E} is the wind velocity in that plane at draft base, at which level the horizontal draft speed is assumed equal to the wind speed.

The horizontal draft velocity $u_d(z)$ may be specified by a horizontal momentum equation analogous to (4), namely

$$d(Mu_d) = u_E\,dM_i - u_d\,dM_0 + \sum F_H, \qquad (11)$$

where the only forces operating to alter the horizontal momentum of the draft are resistances. The horizontal form-drag term $\sum F_H$ will be omitted, and the validity of the omission tested by results of the calculations made without it.

Upon substitution of $dM = dM_i - dM_0$, and division by dz, (11) becomes

$$\frac{du_d}{dz} = (u_d - u_E)\frac{1}{M}\frac{dM_i}{dz}, \qquad (12)$$

which may be integrated stepwise over layers where the external wind shear du_E/dz and the gross entrainment $(1/M)\,dM_i/dz$ are constant. If we start at draft base, where $u_d = u_{E0}$, and substitute the resulting form of $u_d(z)$ into (10), we have

$$\tan\theta = \frac{w_d}{u_d - u_{E0}} = \frac{w_d}{u_d - u_E + bz} = \frac{w_d}{bz + (b/R)(e^{-Rz} - 1)}, \qquad (13)$$

where b is the external wind shear du_E/dz, and R is the proportional gross-entrainment rate $(1/M)\,dM_i/dz$. For upper layers in the draft, where R and du_E/dz may have altered values, the new boundary condition gives a somewhat more complicated-looking solution to (12) which has been derived in the earlier paper by Malkus (1952b). Both forms will be used to calculate the slopes of the clouds studied. The present application will consist of finding the relative draft-air horizontal velocity, $u_d - u_E$, on the basis of the observed wind shear and considering that the measured gross entrainment is the only horizontal resistance. The cloud (draft) slope computed on this hypothesis is then to be compared to that photographed. If the observed cloud slants more than the amount computed, it may be inferred that the exchange of horizontal momentum with the surroundings is greater than stated by (12) and that significant horizontal form drag is operative. If the cloud should slant noticeably less than the amount computed, it may be inferred that something is wrong either with the observations or with the model.

Although studied later in time, the more active cloud is called cloud I. It will be discussed first, and in more detail, as the pertinent data are more complete and the steady-state model calculations more satisfactory.

4. Cloud I, 28 June 1952

This cloud, photographed in the plane of the wind, is shown in fig. 2. It is seen to be a rather isolated cloud, larger than most of its neighbors, although not so large as one or two clouds seen at the same time which had reached cumulonimbus proportions. The airplane was able to make five traverses through the cloud and one

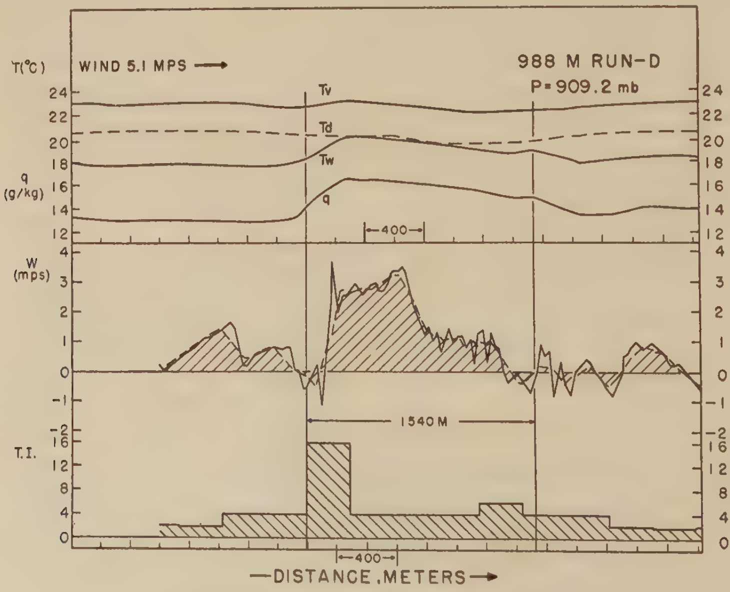

FIG. 7. 988-m run through cloud I. Notation same as in fig. 4.

TABLE 1. Gross entrainment, cloud I.

Level (m)	Pressure (mb)	$\bar{T}$ draft (deg C)	$\bar{q}$ draft (g/kg)	T env. (deg C)	q env. (g/kg)	$\frac{\Delta M}{M_0}$	$\frac{1}{M_0}\frac{\Delta M}{\Delta z}=\frac{1}{M}\frac{dM_i}{dz}$ (10^{-6} cm^{-1})	Increment of liquid water (g/kg)	Wind shear (m sec^{-1} km^{-1})
665	944.1	22.1	17.4	22.2	17.0				
830	926.0	20.5	16.6	20.6	15.8 to 16.0	1.0 to 1.2	6.0 to 7.6	0 to minus trace	3.65
988	909.2	19.5	16.0	20.4	14.0 to 14.8	.23 to .47	1.4 to 3.0	0.1 to trace	−1.90
1108	895.8	18.95	15.5	19.0	13.5 to 14.5	.12 to .23	1.0 to 1.95	≈0.25	−1.66
1296	876.2	17.9	14.8	17.6	13.7 to 14.2	.33 to .60	1.8 to 3.2	0.50 to 0.40	−6.00
1522	853.5	16.1	13.5	15.8	12.5 to 12.8	1.0 to 1.4	4.4 to 6.1	0.40 to 0.30	−6.00

just below its base in less than 25 min; and the cloud, when last seen nearly 1 hr after fig. 2 was made, was still vigorous and maintained the same general appearance. A summary of all the data obtained for this cloud is shown in fig. 3. The original records were side-marked in code to indicate entrance into and exit from the liquid cloud, and it proved extremely easy to fit together the runs at various levels on the silhouette obtained from the photograph. It should be noted how this automatically led to excellent coincidence between the observed draft structure and the major features of the cloud as shown in the photograph. Strong drafts coincide with observed turrets and are consistently traceable from level to level.

Figs. 4–9 give the individual runs at each height. It is interesting that at 830 m and below, several smaller drafts have replaced the fewer and larger ones found on the traverses at higher levels. It is also interesting that, from about 830 m downward, vertical holes through the base of the cloud were clearly visible. These features appeared common to nearly all the good-sized trade cumuli studied, and indicate that the larger clouds may have been formed by an aggregation of several small ones.

The results of the calculations cited in the foregoing section are next to be discussed.

Entrainment calculation.—The calculation of gross entrainment by Stommel's method is given in table 1 and fig. 10. It is important to point out that it is now possible to carry out this calculation specifically for the main draft in the cloud. This is significantly better than the earlier way, in which it was only possible to compare clear air to cloudy air.

Stommel's model envisages the rise of air in a steady-state updraft between levels z and $z + \Delta z$ as follows. The properties within the draft at level z are a mass flux M_0, a temperature T, mixing ratio q, and concentration of liquid water, W. At $z + \Delta z$, the mass flux in the draft is $M_0 + \Delta M$; the temperature is $T + \Delta T$; the mixing ratio is $q + \Delta q$; and the liquid-water content is $W + \Delta W$. In ascending from z to $z + \Delta z$, the draft undergoes a rather complex transformation which may be replaced by three simple steps. First, the temperature decreases because of the adi-

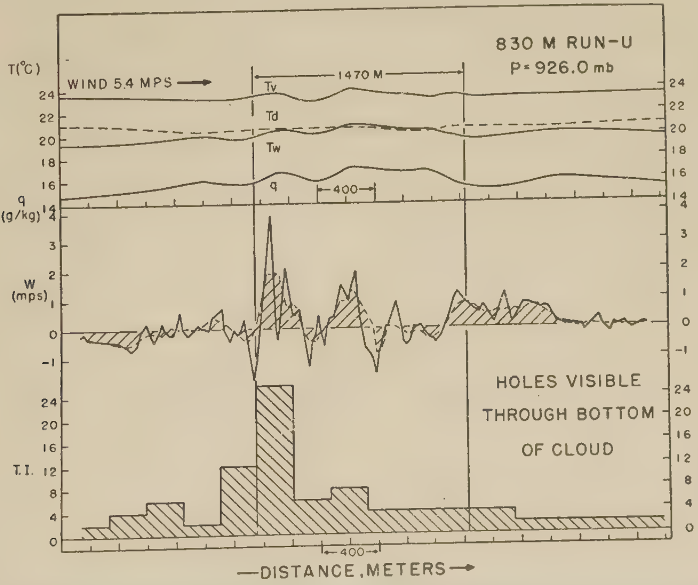

FIG. 8. 830-m run through cloud I. Notation same as in fig. 4. Note that updrafts are separated into smaller individuals at this level, and so are peaks in temperature and moisture records. Note also greater "waviness" of latter records outside cloud boundaries. Value "24" of turbulence index associated with left-hand cloud draft is one of highest values observed during 1952 trip.

TABLE 2. Momentum calculation, cloud I.

Level (m)	Pressure (mb)	$\rho \times 10^3$ (g/cm³)	T_v parcel (deg K)	$\bar{T}_v$ draft (deg K)	$\bar{T}_v'$ env. (deg K)	a (cm/sec²)	Draft diameter (m)	$\frac{1}{A}\frac{dA}{dz}$ (10^{-4} cm⁻¹)	$\bar{w}_{d0}$ (cm/sec)	$a/\bar{w}_{d0}^2$ (10^{-4} cm⁻¹)	Δw_d (cm/sec)	$\bar{w}_d$ (cm/sec)
665	944.1	1.104	298.1	298.1	298.1	0	(2 drafts) 820		40			
						(.331)		0		2.07	68	
830	926.0	1.088	297.9	296.5	296.3	.662	(2 drafts) 820		108			108
						(.742)		−.298		.638	80	
988	909.2	1.071	297.1	295.8	295.55	.822	640		188			188
						(.577)		.122		.162	4	
1108	895.8	1.06	296.6	294.8	294.7	.332	700		192			192
						(1.87)		.142		.510	68	
1296	876.2	1.04	295.8	293.6	292.6	3.42	800		260			260
						(2.72)		.160		.400	70	
1522	853.5	1.02	294.9	291.5	290.9	2.02	960					330

abatic decrease of pressure. Second, outside air is entrained and mixed with the cloud at level $z + \Delta z$. Third, a phase change achieves equilibrium between vapor and liquid phases.

These three steps are represented graphically in fig. 10, on which are plotted the temperatures *versus* mixing ratios of draft and environment at each level. The properties for the draft were found from figs. 4–9, by averaging across the major updraft, defined previously. The range of values in the mixing ratio of the environment, q_{env}, is not due to instrumental uncertainty, but to the fact that on one side of the updraft was clear air and on the other side was moister cloudy air. The extreme range was therefore considered.

In fig. 10, if we take the draft air at any level z, the first step of adiabatic cooling is represented by the vertical line toward decreasing temperature. If no condensation occurred, the new draft image point would lie on the line joining the bottom of the vertical line to the point representing the environment, being the nearer the environment point the greater the mixing. This line is called the mixing line. Actually, in general, condensation takes place, resulting in warming and loss of water vapor in a known ratio, namely $dT/dq = -L/c_p \approx -2.5 \times 10^3$C, where L is the latent heat of condensation, c_p the specific heat of air at constant pressure, and the mixing ratio is in g/g. The final result of this condensation must give the observed draft properties at the level $z + \Delta z$. Thus, the ratio of air drawn in from the environment to that already contained in the draft, $(\Delta M)/M_0$, is found by constructing the line of slope -2.5 from the point representing the observed draft properties until it intersects the mixing line. The length of the mixing line to the right of the intersection is proportional to ΔM, and the length of the mixing line to the left is proportional to M_0. The gross entrainment $(1/M)\,dM_i/dz$ is found by dividing the ratio $(\Delta M)/M_0$ by Δz. The increment

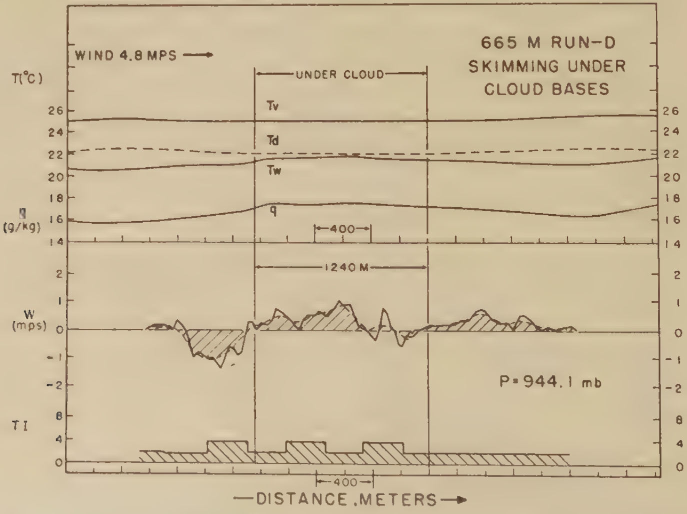

FIG. 9. 665-m run just under base of cloud I (in clear air, skimming cloud bottom). Notation same as in fig. 4, except that vertical lines define that part of record made directly under, rather than within, cloud. Note extreme flatness of T_v curve, showing no buoyancy whatsoever beneath cloud. There is also no excess turbulence beneath cloud, and no "roots" of any kind are detectable. According to conversation with Mr. Bunker, vertical drafts of 40–60 cm/sec are rule, not exception, in clear air away from clouds at this level.

TABLE 3. Comparisons, cloud I.

Level (m)	Calc. $\overline{w}_d$ (cm/sec)	Obs. $\overline{w}_d$ (cm/sec)	Parcel w_p (cm/sec)	Mass flux calc. $\overline{w}_d$ (10^8g/sec)	Mass flux obs. $\overline{w}_d$ (10^8g/sec)	Dynamic entrain. calc. $\overline{w}_d$ (10^{-5}cm^{-1})	Dynamic entrain. obs. $\overline{w}_d$ (10^{-5}cm^{-1})	Gross entrainment (10^{-5}cm^{-1})	Difference gross minus dyn. calc. $\overline{w}_d$ (10^{-5}cm^{-1})	Difference gross minus dyn. obs. $\overline{w}_d$ (10^{-5}cm^{-1})	Shear (m sec^{-1}km^{-1})
665	(40)	40	(40)		2.34						
830	108	80	1070	6.15	4.56	5.4	3.9	6.0 to 7.6	0.6 to 2.2	2.1 to 3.7	3.65
988	188	200	1147	6.46	6.88	0.3	2.6	1.4 to 3.0	1.3 to 2.7	−1.2 to 0.4	−1.90
1108	192	120	1207	7.82	4.90	1.6	−2.8	1.0 to 1.95	−0.6 to 0.35	3.8 to 4.7	−1.66
1296	260	270	1334	13.60	14.11	2.9	5.1	1.8 to 3.2	−1.1 to 0.3	−3.3 to −1.9	−6.00
1522	330	325	1563	24.36	23.80	2.5	2.3	4.4 to 6.1	1.9 to 3.6	2.1 to 3.8	−6.00

of liquid water from one level to the next is found simply as the difference in q between the point on the mixing line and the corresponding observed draft point, *i.e.*, the amount of vapor condensed at each step. These values appear in the second column from the right in table 1. The values of gross entrainment, $(1/M)\ dM_i/dz$, found in the table are quite comparable to those obtained from the work of Stommel (1947; see also Malkus, 1952b). The large values at the lowest and uppermost levels of the cloud will be elucidated in table 3, when dynamic entrainment is compared to gross entrainment. Prior to this comparison, however, the momentum calculation will be discussed.

Momentum calculation.—Table 2 gives the calculated updraft speed at each level, based on (6). The virtual temperatures and draft diameters were taken from figs. 4–9. The cross-sectional draft area was obtained by assumption of circular drafts. The $\overline{w}_{d0}$ at 665 m represents the graphically averaged (across the draft diameter), observed vertical draft speed at that level. The values of buoyancy, α, contained in the parentheses, are means between each of the two successive levels. The densities, ρ, were calculated from the equation of state, and all the remainder of the quantities except the parcel T_v, by successive applications of (6). The virtual temperature which would be characteristic of the unmixed parcel, T_v parcel, was obtained from an adiabatic diagram, using the moist adiabat which intersects the sounding at cloud base.

Comparisons and discussion.—The final results of the calculations are summarized and compared in table 3. It is important to note the very good agreement between the measured mean updraft speeds and those calculated using (6). With the exception of the 1108-m level, the departures between observed and calculated values do not exceed 28 cm/sec, which is almost the accuracy of the draft observations. As for the 1108-m level, the columns showing total and dynamic entrainment and mass flux may indicate that the measured draft speed at that level is erroneously low. If the airplane were diving rather than levelled out when the run was begun, such an error could have resulted. By commencing the integration later, rather than at the point on the accelerometer record marked "start," higher draft velocities would have been obtained. This, however, represents a departure from the strictly objective way in which all the remaining data were reduced, and therefore seems undesirable, especially since corrections for attitude variations and accurate zeros will be obtained on all future flights.

The third column from the left shows the vertical ascent rate of an unmixed parcel rising moist adiabatically from the cloud base. Its speed was calculated from (9), using a w_p of 40 cm/sec at cloud base. At the highest level studied, 1522 m (see fig. 4), the unmixed parcel would have an upward speed of over 15 m/sec, nearly *five* times the observed and calculated mean draft speeds, which almost exactly coincide. The maximum observed upward speed is about 4.5 m/sec (±50 cm/sec). Since the accelerometer records were read at ½-sec intervals (approximately 25-m distance intervals), non-interacting parcels this size or larger rising from cloud base are almost surely precluded. A detailed comparison (see Brewer, 1954) of the water-column accelerometer used in this study with a highly sensitive electric accelerometer (response better than 1/60 sec) and with a direct study of the gust loads imposed on the aircraft wings demonstrates conclusively

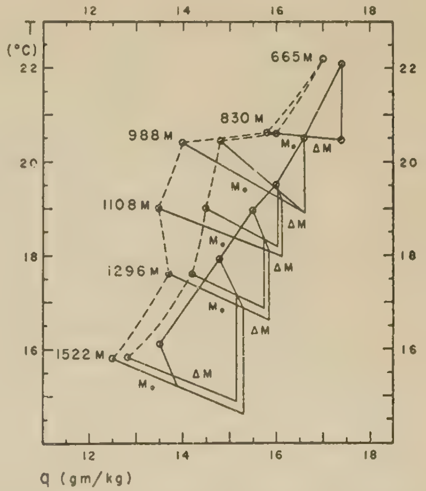

FIG. 10. Graph showing entrainment calculation for major updraft, cloud I, 28 June 1952. Solid curve gives measured mean values of temperature plotted against mixing ratio within draft, at each of six levels indicated. Two dashed curves give measured extreme range in these properties for draft environment. Vertical lines represent hypothetical stage of adiabatic cooling as draft air rises from z to $z + \Delta z$, and quasi-horizontal line joining bottom of vertical line to environment point is mixing line. Steps are described in more detail in text.

that, if such velocity fluctuations had existed, they would have been detected by the present method.

It is now also possible to make the projected comparison between the dynamic entrainment defined by (3) and the gross entrainment found by Stommel's method from psychrograph records. The results are extremely consistent and satisfactory. The high value of gross entrainment between the cloud base and 830 m is seen to be equalled or nearly equalled by the influx required to meet mass continuity. The fact that the mass flux increases by a factor of two or three between 665 and 830 m indeed supports earlier ideas that trade cumuli obtain most of their air from within the cloud layer, and not from the subcloud levels.

The height interval through which the gross entrainment greatly exceeds dynamic entrainment is the topmost (1296–1522 m), where the wind shear is very large and the cloud has a pronounced backslant. This implies that the proportional rate of efflux, $(1/M)\, dM_0/dz$, is largest here, or that the air is moving most rapidly through the cloud, as hypothesized previously by Malkus (1952a). The average value of $(1/M)\, dM_0/dz$ in this layer is about 2.5×10^{-5} cm^{-1}. Since the corresponding average mass flux within the draft is about 19×10^8 g/sec, this gives an exiting mass flux of approximately 10.7×10^8 g/sec, or a little more than half that rising in the draft. If it can be thought that the influx occurs largely on the upshear side of the draft, and the efflux on the downshear side, this represents an average rate of flow "through" the draft of the order of 5 m/sec at these heights. In other words, the implication is that about 180 sec or 3 min would be required for air to travel all the way through the cloud horizontally. If a hypothetical group of molecules started on the upshear edge of the draft at 1296 m, and rose at 3 m/sec, it would be ejected from the downshear edge 540 m higher up, or at about 1840 m, which is just short of the cloud top.

We may now make the second test of the assumption that the change with height experienced by the vertical momentum of the draft is largely created by buoyancy forces. This is done by application of (7) to the data in table 3. For all height intervals up to the topmost, the excess of gross over dynamic entrainment averages only about 12 per cent; hence, in these regions, dM_0 is not much different from zero. Equation (7) thus implies that w_E is very nearly zero on the average. Examination of figs. 5–9, with attention to the weak up- and down-drafts in the near neighborhood of the major draft, indicates that a mean $w_E \approx 0$ is indeed consistent with the data. Thus, in the lowest 700 m of the cloud the steady-state model gives self-consistent verifiable results, as does the additional hypothesis concerning the smallness of momentum exchange between draft and surroundings. So it may be inferred that form drag in the vertical was indeed negligible in these height ranges, since the calculated vertical motions showed no tendency systematically to exceed those observed. This is indeed to be expected in the quasi-steady phase of a cumulus cloud's life cycle, and in its central and lower portions. It has been pointed out by Schmidt (1947) that form drag in the vertical would be caused mainly by the ascending tower's pushing aside air as it rises and establishes a countercurrent. The cloud top in the case of cloud I was some 600 m higher than the upper part of the region under discussion.

In the uppermost layer investigated, 1296–1522 m, it was seen that gross entrainment significantly exceeded dynamic entrainment, and that dM_0 was quite different from zero. Application of (7) tells us that, for (6) to be applicable, w_E must average about $+1$ m/sec. Examination of figs. 4 and 5 does not definitely preclude this possibility, although the indication is very strong that w_E should not exceed about $+50$ cm/sec. If this latter value is taken, and (8) is applied to calculate the vertical draft velocity at 1522 m, the result is only 284 cm/sec, compared to the observed value of 325 cm/sec or the value of 330 cm/sec calculated from (6). Although a 40-cm/sec or 13-per cent error in w is not serious, it perhaps indicates that at the upper levels of the cloud the steady-state model begins to become internally inconsistent. It would obviously be folly to attempt to apply it to the more rapidly growing and decaying tower portions. Thus, to state anything about vertical form drag at upper levels would be hazardous on the basis of the present work. Clearly such drag must be important in the growing phases of a tower.

Slope calculation.—The slope of the draft in the plane of the wind may now be calculated, using the method outlined in section 3, above. The results of this calculation are presented in table 4.

This computation involves obtaining the relative draft-air horizontal velocity, $u_d - u_E$, at each level. This quantity is positive when the draft moves downwind faster than the external wind, u_E, and was assumed to be zero at cloud base (665 m), implying that the draft had no roots below this level. As is shown by (12), $u_d - u_E$ depends critically on the horizontal resistance forces operating upon the draft. Table 4 is calculated by use of (13), with the assumption that gross entrainment serves as the only horizontal resistance. The ranges given in draft-air velocity, $u_d - u_E$, and in departure of draft horizontal velocity from the windspeed at cloud base, $u_d - u_{E0}$, and thus in slope, are due to possible ranges in the proportional rate of entrainment, $(1/M)\, dM_i/dz$, which has been discussed previously.

Inspection of that column in Table 4 marked $u_d - u_E$ shows that the horizontal motion of the draft is downwind slower than the outside air at 830 m, nearly the same as the outside air at 988 m, and faster than the wind at each higher level. The relative velocities are

TABLE 4. Slope calculation, cloud I.

Level (m)	$\frac{1}{M}\frac{dM_i}{dz}$ (10^{-5} cm^{-1})	$u_E - u_{0E}$ (cm/sec)	$u_d - u_E$ (cm/sec)	$u_d - u_{0E}$ (cm/sec)	$\bar{w}_d$ (calc.) (cm/sec)	Slope = $\frac{\bar{w}_d \text{ (calc.)}}{u_d - u_{0E}}$	Slope using mean $\frac{1}{M}\frac{dM_i}{dz}$
665	6.0 to 7.6						
830	1.4 to 3.0	59.4	−38.2 to −34.2	21.2 to 25.5	108	5.1 to 4.3	4.5
988	1.0 to 1.95	30.0	− 4.1 to 2.9	26.0 to 33.0	188	7.2 to 5.7	6.2
1108	1.8 to 3.2	10.0	15.3 to 20.4	25.3 to 30.4	192	7.6 to 6.3	6.7
1296	4.4 to 6.1	−100.0	106 to 95.5	3.0 to −7.5	260	86 to −35	∞
1522		−240.0	125 to 97.5	−115 to −142.5	330	−2.9 to − 2.3	−2.6

fairly large, equalling or exceeding 1 m/sec at the two upper levels.

The slope calculated in the last column of table 4 is plotted on the silhouette of the cloud which was given in fig. 3. Fig. 11 shows a more detailed consideration of slopes. The two light, solid lines to right and left of the heavy curved solid line show the range in slopes indicated in the next-to-last column of table 4. It was also desired to gauge the effect of additional resistance forces in the horizontal, such as form drag, upon the slope. The dashed lines in fig. 11 show the slope the draft would exhibit at each level if an additional resistance were operative, equivalent to a proportional entrainment rate of 2×10^{-5} cm^{-1} [see Malkus, 1952b, equation (13) and discussion, and also section 2b], in addition to the maximum entrainment rate of table 4. The arrows at the extreme right in fig. 11 show the slope at each level that would obtain if the resistance represented by the mean entrainment were doubled, thus allowing for a form-drag resistance force equal to that provided by entrainment. Although at 830 and 1522 m the cloud does not slant as much as the arrows, a slope drawn through the dashed lines clearly is not precluded. Thus, a horizontal form-drag coefficient of 2×10^{-5} cm^{-1} or somewhat larger may have been operative. Since the cloud slant is only slightly altered by rather large changes in horizontal resistance, it probably will not be possible to specify the resistance any more accurately than this by the slope method.

5. Cloud II, 28 June 1952

This cloud, photographed in the plane of the wind, is shown in fig. 12. It is the largest member of a cluster of clouds. The airplane was able to complete seven traverses through the cloud in 20 min, at the end of which the cloud's appearance had changed relatively little. A summary of the draft structure within this

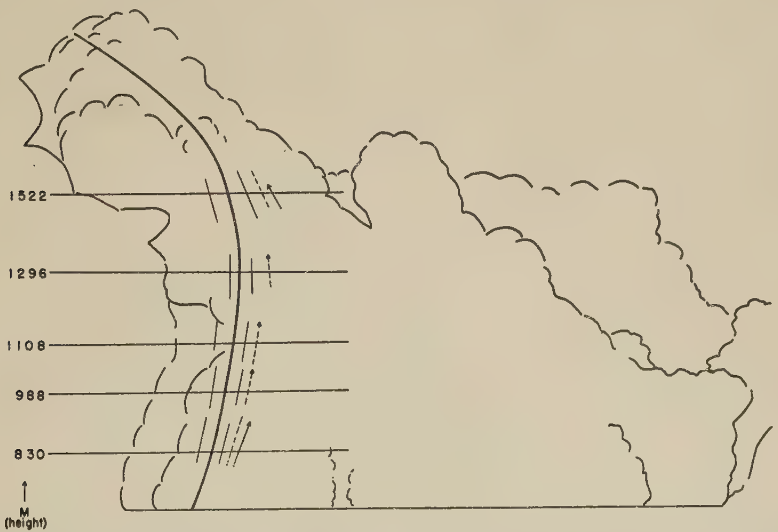

FIG. 11. Schematic diagram of varying slopes for cloud I. Heavy solid curve is slope given by last column in table 4. Light solid lines on either side of this curve are slopes shown in next-to-last column of table 4; *i.e.*, possible range due to possible range in entrainment rates (depending on relative entrainment from the two sides of draft). Dashed line is slope which would obtain at each level if additional resistance equivalent to proportional entrainment rate of 2×10^{-5} cm^{-1} were added to maximum entrainment rate shown in next-to-last column of table 4. In other words, dashed lines represent slope the draft would have if, in addition to maximum amount of mixing, a form drag force of sizable amount were added. Arrows show slope which would obtain if mean entrainment rate were doubled, or if a form drag force were added which was just as great as resistance due to mean value of entrainment. Where dashed lines and arrows would very nearly coincide, they are indicated by single dashed arrow. Cloud silhouette in background is drawn to scale from photograph.

cloud is shown in fig. 13, with the exception of the run made at 1450 m, which was not flown quite along the same course. It was possible to construct only the upper part of the cloud silhouette (containing the topmost two runs) from the photograph; the rest of the cloud has been put together with use of the slope which was later calculated from the data. Three of the individual runs, from top to bottom, are shown in figs. 14–16.

It is interesting to note that the drafts in this cloud also appear to undergo a transition toward greater numbers and smaller size as the 830-m level is reached on the descent. It was at this level that the observer began to record vertical holes in the cloud, which permitted the sea surface to be seen clearly although the airplane was still surrounded horizontally by cloud matter. This cloud was clearly in a later stage of its life cycle than cloud I, exhibiting only downdrafts on the uppermost run and a very strong downdraft, of nearly 4 m/sec, on the next-to-uppermost run at 1554 m. It therefore seemed very doubtful at first whether calculations based on the steady-state cloud model would have any meaning in this case. When, however, they were made speparately for updraft and for downdraft, it was found that the computed quantities were very consistent and agreed rather well with observed values, although with not such good agreement as was found in the case of cloud I. Since the calculations were made in a similar manner to those for the preceding cloud, only the results will be summarized in the discussion.

Results of calculations for updraft.—The results of the same calculations as for cloud I performed on the major updraft in cloud II are presented in table 5. In addition to the 1450-m run, the 1126-m run was omitted since it penetrated only the edge of the draft.

Up to 1296 m, the steady-state model again proves fairly adequate and internally consistent. From 830–988 m, the dynamic and gross entrainment are very nearly equal, implying a $w_E \approx 0$, which is consistent with, if not definitely established by, the data. From 988–1296 m, a value of $(1/M)\, dM_0/dz$ of about 1.5×10^{-5} cm^{-1} is indicated, implying a $w_E \approx +60$ cm/sec for (6) to hold. The presence of smaller neighboring updrafts at these levels on fig. 13 makes this plausible. The values of w_d calculated from (6), although fairly

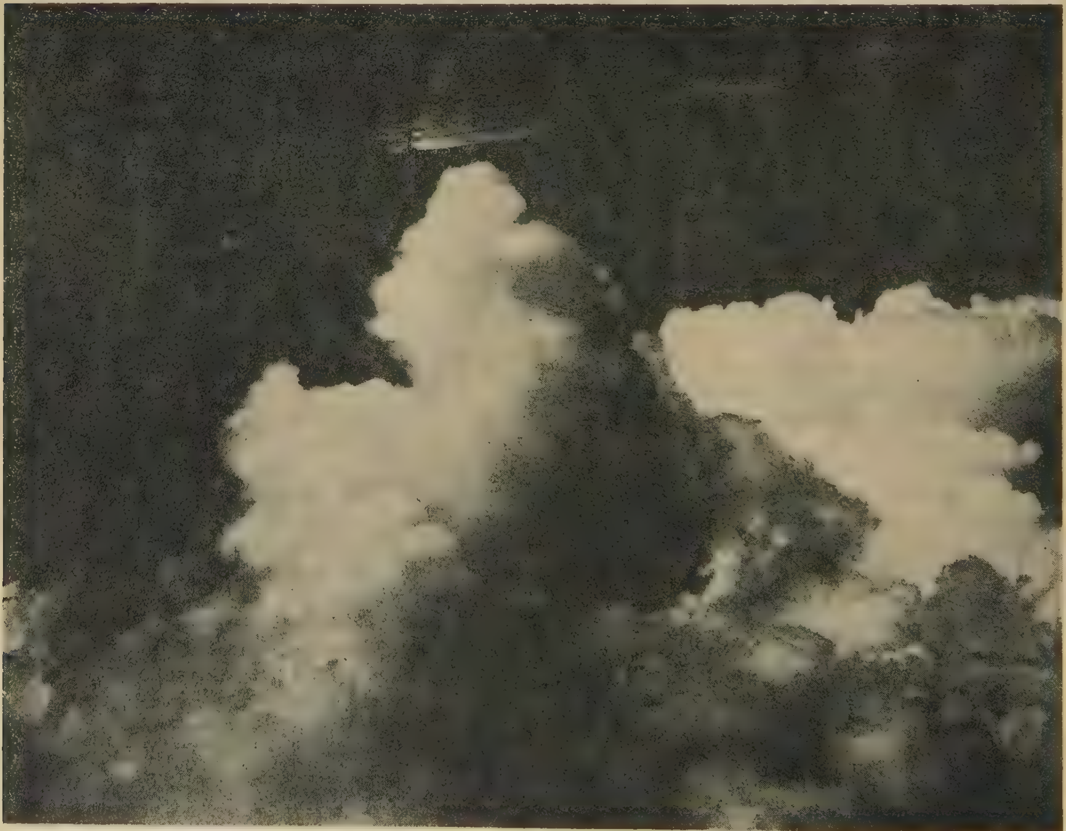

FIG. 12. Photograph, in plane of wind, of upper portions of cloud II. Wind blows from left (east-southeast) to right across picture.

Table 5. Calculations for the updraft, cloud II.

Level (m)	$\bar{T}_v$ draft (deg K)	$\bar{T}_v$ env. (deg K)	α (cm/sec²)	Draft diameter (m)	Δw (cm/sec)	w_{calc} (cm/sec)	w_{obs} (cm/sec)	M (obs) (10^8 g/sec)	$\frac{1}{M}\frac{dM}{ds}$ (10^{-5} cm⁻¹)	$\frac{1}{M}\frac{dM_l}{ds}$ (10^{-5} cm⁻¹)	Increment of liquid water (g/kg)	External shear (m sec⁻¹ km⁻¹)
830	297.6	297.3	0.99	340			140	1.4				
			(1.46)		53				5.1	1.8–4.9	0.2	+2.3
988	296.6	296.0	1.94	420		193	220	3.25				
			(0.72)		−69				0.85	2.1–3.3	0.4	−2.2
1296	293.6	293.75	−0.50	760		124	90	4.2				
			(−0.08)		51				−1.75	2.5–3.6	0.65	−2.3
1554	291.55	291.45	0.34	440		175	170	2.64				
			(−0.52)		−118				?	9.0	0.15	−2.4*
1686	291.5	291.7	−1.37	800		57	−160	?				

* Extrapolated above 1600 m.

close to those observed, are 15 and 30 per cent off at 988 and 1296 m, respectively, which is considerably worse than the agreement at corresponding levels of cloud I.

Above 1296 m, the model encounters only slightly worse trouble. Between 1296 m and 1554 m, if (6) is to hold, w_E must be of the same magnitude as the velocity of the draft itself, or about +150 cm/sec. The data almost entirely eliminate this possibility. If, on the other hand, a w_E of +50 cm/sec, which the data suggest, is used in (8), the value of w_d at 1554 m becomes 125 cm/sec, compared to 170 cm/sec observed, or an error of about 26 per cent. In the topmost layer, the inadequacy of (6) is plainly indicated by a comparison of the computed decrease of w_d between 1554 and 1686 m to that observed. Examination of fig. 13 suggests a w_E of about −1 m/sec, which when used in (8) gives a decrease in w of 336 cm/sec, which is in very good agreement with the observed decrease.

Thus it may be seen that, while the steady-state model seems to apply somewhat more poorly to this updraft as a whole than in the case of cloud I, it is not significantly worse in the upper levels. The reason may lie in the observations. From the PBY pilot's point of view, this cloud was far more difficult to contend with, because it was one of a cluster of several clouds close together. Equation (6), however, is clearly not applicable in this latter case above 1296 m, since air of lower upward momentum is found to be entering the draft by entrainment and retarding it. The slope calculation for this draft is not presented, since there was no observed slope to check it against. The mean calculated slope was used, however, to construct fig. 13 and is given by the heavy solid lines therein.

Results of calculations for downdraft.—The downdraft extended from the topmost run at 1686 m perhaps down to 1296 m, where it is bearly perceptible on fig. 13. The results of the calculations for it are presented in table 6. Stommel's method for calculating entrainment was modified readily to apply to downdrafts and evaporation of liquid water. In calculating the entrainment from one level to the next lower one,

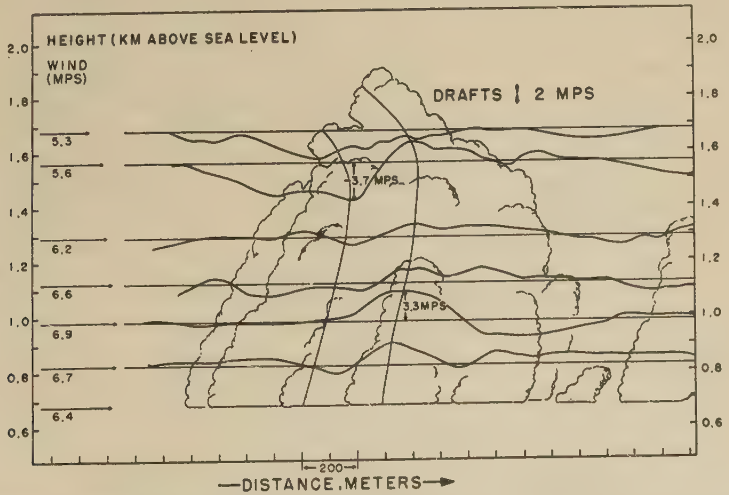

Fig. 13. Summary of draft structure for cloud II, put together at upper levels with aid of photograph (fig. 12) and at lower levels by using computed slope. Solid curves are drafts when running average over 150-m distances is taken. Origin is thin horizontal line at each level. Note predominance of downdrafts in upper levels.

TABLE 6. Calculations for downdraft, cloud II.

Level (m)	$\bar{T}_v$ draft (deg K)	$\bar{T}_v$ env. (deg K)	a (cm/sec²)	Draft diameter (m)	Δw (cm/sec)	w_{calc} (cm/sec)	w_{obs} (cm/sec)	M_{obs} (10^8 g/sec)	$\frac{1}{M}\frac{dM_i}{dz}$ from updraft (10^{-5} cm^{-1})	$\frac{1}{M}\frac{dM_i}{dz}$ mixture (10^{-5} cm^{-1})	$\frac{1}{M}\frac{dM}{dz}$ (10^{-5} cm^{-1})	Evap. Δw (g/kg)
1686	291.1	291.5	−1.37	800			−160	8.05				
			(−1.02)		−60				2	4.4	1.3	0.3
1554	291.5	291.7	−0.675	720		−220	−230	9.54				
									22.2	→ ∞		0.2
1296				200(?)	Draft essentially disappeared							

the problem arose that the environment of the downdraft differed radically, ranging from relatively dry, clear air on the upwind side to very moist, cloudy updraft air on the downwind side. It is immediately evident that the downdraft cannot be mixing solely with clear air, as the calculation shows no possible admixture between clear air and air initially in the draft which can give rise to the observed temperatures and moistures found within the draft at the next lower level. The fourth column from the right in table 6 gives the gross entrainment in the downdraft, calculated on the assumption that the air entrained came entirely from the updraft side; the third column from the right shows the gross entrainment occurring if the downdraft was entraining symmetrically, one-half the influx coming from each side. It has been hypothesized by Malkus (1949; 1952a) that air should be moving through an updraft in the direction pointed by the shear vector (in this case upwind), and thus it seems likely that this downdraft should consist primarily of air which was previously in the updraft. The plausibility of this contention is not undermined by the results shown in table 6. It appears from the very large computed value of $(1/M)\,dM_i/dz$ between the 1554-m level and 1296 m that, at 1296 m, the downdraft had either nearly lost its identity or had not yet penetrated. The last column in table 6 gives the quantity of liquid water which must have been evaporated from the cloudy downdraft between successive levels. This varied only negligibly with varying proportions entrained from clear and cloudy air.

The momentum calculation for the downdraft with use of (6) gives apparently quite good results for the downward acceleration of the draft between 1686 and 1554 m. If the test of (7) is used, however, a w_E of about −70 cm/sec is required, which is inconsistent with the hypothesis that the entrained air is coming largely from the updraft. If, consistent with the latter, a w_E of +50 cm/sec is taken and (8) applied, a $\Delta w_d \approx 0$ between 1686 m and 1554 m results, giving a 30-per cent error in w_d at 1554 m. Since the observer noted that the visible cloud tower was actually descending from one run to the next, it is probable that a local downward acceleration with time was present in the downdraft, thus giving a rather poor prognosis for the applicability of a steady-state model to this portion of the cloud. Even so, the results are not highly unsatisfactory.

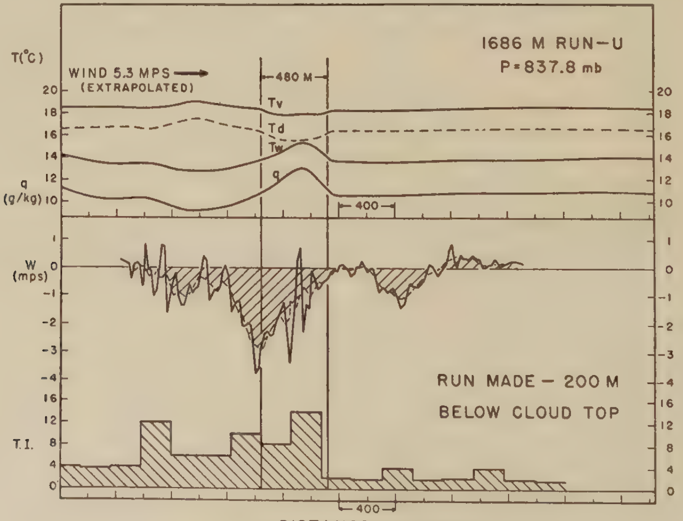

FIG. 14. 1686-m run through cloud II. Notation same as in fig. 4. Note lower virtual temperature (negative buoyancy) within cloud.

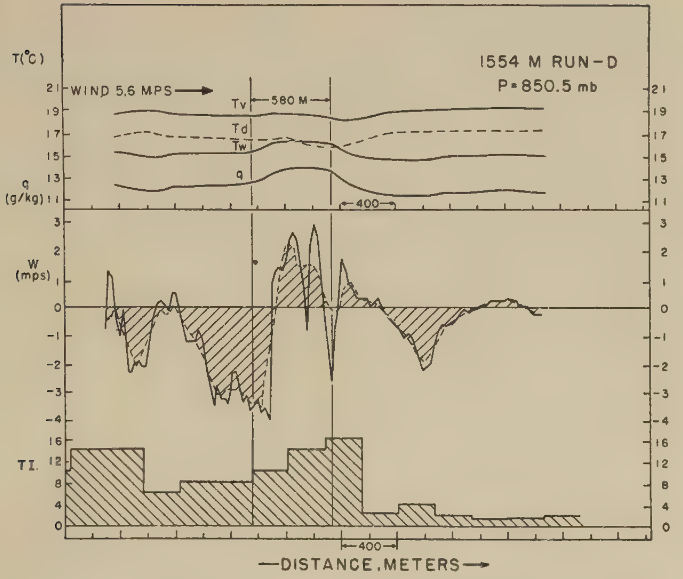

FIG. 15. 1554-m run through cloud II. Notation same as in fig. 4. This downdraft (nearly 4 m/sec) was strongest observed on 1952 trip.

6. Comparison of the two clouds and their environments

Cloud II was studied at 1500 Local Standard Time and was located about 10 mi southwest of St. Croix, V. I. Cloud I was studied at 1630 LST and was located about 30 mi southwest of St. Croix. About halfway between the two cloud investigations in both time and space, a clear-air spiral sounding was made, at 1535 LST and 20 mi southwest of St. Croix. The wind directions between 1000 and 5000 ft ranged between 140 and 110 deg on this particular afternoon; hence, the air in the area studied cannot have been affected by flow over the island.

The clear-air sounding is reproduced in fig. 17, and is quite typical of the area for June. The termination of the smaller clouds at about 1100 m, and the relative

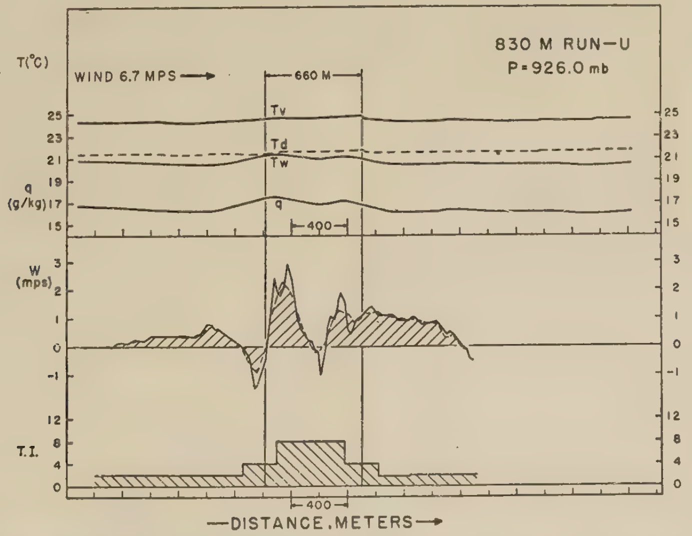

FIG. 16. 830-m run through cloud II. Notation same as in fig. 4. This was lowest run made through cloud II. Note that draft, moisture and temperature curves are also starting to separate into more small peaks at this level. Holes were seen from here down to sea surface.

weakness at that level of the two clouds described here, become understandable in terms of the rather stable, dry air-layer occurring at that height.

It was desired to test how nearly the clear air immediately adjacent to cloud I and cloud II resembled the clear-air sounding in temperature and moisture content. For that reason, the environment temperatures and moistures of cloud I are plotted as crosses on fig. 17, while the values immediately adjacent to cloud II are indicated by dark triangles at the appropriate levels. The environment of cloud I, it will be noted, differs imperceptibly from the clear-air sounding, except for the reduction of the extremely dry layer at 1100 m. This appears to indicate that cloud I is the first tall cloud to grow in its locality, a supposition which is supported by its isolation. The environment of cloud II, on the other hand, is both warmer and wetter than the air penetrated by the sounding, and the excessive moisture up to 1450 m is its striking feature. This might indicate that predecessors of cloud II had wetted the air in that locality, thus facilitating the growth of cloud II up to an even greater height.

An interesting calculation sheds more light upon the importance of small differences in cloud environment. A hypothetical cloud was considered to grow in the air described by the sounding in fig. 17. It was arbitrarily given the same temperature and moisture excess over the clear-air sounding at 830 m as cloud II was observed to possess over its environment at that level. Upon the use of a few reasonable assumptions concerning entrainment and condensation rates, it was found that such a cloud would be a very feeble one indeed, possessing no average draft greater than 1.2 m/sec (at 1296 m) and dying out before 1554 m was reached. In other words, it appears that the growth of cloud II was greatly aided by the fact that the air in its environment was considerably wetter than that of the clear-air sounding. It also appears that the successive growths of convective clouds must be considered in understanding the development of very large cumuli. This point was previously made by Braham (1952) when he demonstrated that, compared to the mean July sounding for thunderstorm days in Ohio, the calculated water consumption of a thunderstorm was impossibly large. He thus concluded that the mean sounding must have been modified toward increasing moisture content by pre-thunderstorm convective cloud growth.

7. Concluding remarks

Three types of conclusions may be drawn from the preceding work. The first is that the method of studying cumulus-cloud draft structure by means of a slow-flying aircraft can, after considerable pains, be made to work. Furthermore, the adequacy of the several instrumental procedures is indicated by the very consistent picture produced by the meshing of several completely independent measurements. It can be demonstrated that, if any of these measurements had been seriously in error, no such coherent structure for these two clouds could have appeared.

The second group of conclusions concerns the degree of confirmation of the steady-state draft theories. It appears that the Stommel-Malkus model is applicable to the central portions of at least some clouds and has led to self-consistent verifiable results. The predictions pertaining to entrainment, cloud slopes, lack of trade-cumulus "roots," and relations between asymmetries in updraft structure and wind shear appear to verify in these cases, although more observational evidence is still desirable. It is important to emphasize in this connection the degree of selectivity employed in choosing the two clouds presented. Of the ten observation days constituting the 1952 field trip, only about half produced cumuli through which five or more traverses were possible. Even on the "best" day, 28 June, discussed herein, one out of the total of three clouds selected died during the runs and was omitted from the analysis. On an average day, the airplane was commonly forced to circle for 10–15 min before a promising cloud was sighted. Thus it is not contended that clouds I and II are typical members of the trade-cumulus population, although it seems very likely that a major portion of clouds their size or larger go through

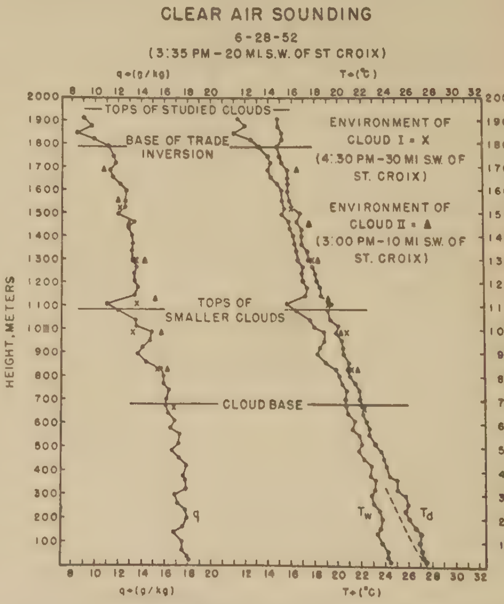

FIG. 17. Clear-air sounding, made using psychrograph in spiral descent about 2 mi in diameter. T_d denotes dry-bulb curve, T_w denotes wet-bulb curve, and mixing-ratio curve is indicated by q. Ordinate gives height in meters, and dashed line next to T_d curve is a dry adiabat.

a quasi-steady phase. Nevertheless, the testing of the present model, even on somewhat atypical clouds, serves the function of establishing the orders of magnitude of the various parameters and forces acting. Equally important, the steady-state model serves to test and establish the soundness of the observational techniques and procedures, which may now be applied with confidence even when the departures from a steady state are large.

Finally, certain suggestions are provided by the data which may contribute eventually to the evolution of a time-dependent cumulus-cloud model. The most striking of these appears to be the interaction of cumuli, both in space and in time. In other words, the formation of a very large cloud seems to imply the aggregation of several small neighboring clouds, and also the precedence in time of earlier cloud towers in the same locality.

Acknowledgments.—The writer desires to emphasize the degree to which the present study is the result of a cooperative venture among many persons. Vitally important were the studies of the flight characteristics of the airplane by Mr. Given A. Brewer; the instrumentation, largely developed and executed by Mr. Kenneth G. McCasland; the maintenance and skillful flying of the aircraft under Chief Pilot Norman Gingrass; and the photography carried out by Mr. Claude Ronne. Contributions were made at all stages of the work by Mr. Andrew F. Bunker, who is responsible for the essentials of the draft-measuring technique.

Last, but by no means least, deep gratitude is due Prof. D. C. MacDowell, of the University of Puerto Rico, without whose energetic and generous participation the field program would have been far less successful.

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Contribution No. 668

Särtryck ur Tellus nr 1, 1954.

Average Temperature and Salinity at a Depth of 200 Meters in the North Atlantic[1]

By F. C. FUGLISTER, Woods Hole Oceanographic Institution

(Manuscript Received October 20, 1953)

Abstract

New charts are presented showing the average temperature and average salinity at a depth of 200 meters in the North Atlantic. These are compared with charts published by WÜST and DEFANT in 1936 and it is shown that, over most of the ocean, conditions are nearly constant at this depth. Attention is focused on the areas of changing temperature where the major ocean currents exist. It is shown that important details are obscured by the averaging process. The range of observed temperature is charted and supplements the information given by the average charts. The standard deviation from the mean temperature, calculated for two portions of the Gulf Stream System, indicates that when more observations are available such calculations may be of use in studying the major ocean current systems. Temperature anomalies from the mean for each degree of latitude are plotted and compared with data published by WÜST in 1937.

Introduction

The best source of information on the subsurface temperature, salinity and density distribution in the North and South Atlantic is the atlas to volume six of the Deutsche Atlantische Expedition Meteor (WÜST and DEFANT, 1936). The atlas contains charts of average conditions for various standard depths from 200 meters to 5,000 meters. These charts represent the mean state or yearly normal and were based on all available data regardless of date. The charts are printed in colors and are large, clear and easy to read. Because virtually all studies of the general circulation of the oceans are based on what is known of the temperature, salinity and density distribution and also because of its exceptional quality this atlas should be a standard reference on the subject.

Since the date of publication of the Meteor Atlas many observations, especially of subsurface temperatures, have been made in the North Atlantic. The files of the Woods Hole Oceanographic Institution contain 210,000 records of subsurface temperatures obtained with the bathythermograph and 37,000 serial observations of subsurface temperature and salinity obtained by the Nansen bottle method. All of the bathythermograph and approximately 50 % of the serial observations were made after 1934. With these new data on hand the question arises as to whether or not that part of the Meteor Atlas that deals with the North Atlantic is obsolete.

The task of producing a new atlas in any way comparable to the German one would

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be an expensive and large undertaking. If it should prove desirable at this time, then the U.S. Navy Hydrographic Office with its punch card system and complete file of data would be best able to do this work. This paper is intended as an investigation of the problem of whether or not a part of the Meteor Atlas is obsolete and it may serve as a supplement to that atlas. Only the 200 meter depth is considered, partly because there are more new data for this than for any other depth represented in the German Atlas and partly because the temperature conditions at this depth have been of special interest in various studies of the Gulf Stream System, (Wüst, 1937) (Fuglister, 1951). Problems that arose in the averaging process will be discussed and the need for other than average charts examined.

Chart Construction

Of the available temperature observations, 40,000 reached to a depth of 200 meters and were used in constructing the accompanying 200 meter average temperature chart (chart 2); 14,000 salinity observations were available for the 200 meter average salinity chart (chart 4). This is approximately 10 times as many temperature observations and 4 times as many salinity observations as were available for the construction of the German Atlas Charts (here copied as charts 1 and 3). Lest it is felt that the saturation point of observations in the North Atlantic is being approached, chart number 5 has been drawn up to show the large portions of this ocean for which our files contain no data for the 200 meter depth.

In the process of averaging, the unit of area used was the one degree field. All observations from one month, regardless of year, were averaged and then these monthly values were in turn averaged to obtain a yearly normal. This system tended to decrease the weight of numerous observations made by one ship at one time in a unit area as it increased the weight of scattered "off season" observations. The temperature and salinity values from serial observations were, in many cases, interpolated values. The tabulations for each unit area included, besides the average temperature and salinity, the total number of observations, the months represented, the maximum and minimum observed values and the range. In order to compare the 200 meter temperature data with some results published by Wüst (1937), the average temperature for each degree of latitude was calculated and the temperature anomalies for each one degree field were tabulated. In these computations the Mediterranean data were excluded.

After the various tabulated values were plotted on the charts an important decision had to be made. Should the isopleths be drawn to follow the plotted values exactly or should some smoothing of the resulting irregular curves be done? Once a smoothing process of this sort is started it is difficult to know where to stop. Rather than risk misinterpreting the data, the decision was made to make every effort to follow the data exactly. An exception was made in a few cases where separate isopleths would have been required to represent a single value unsupported by the values in adjacent one degree fields. Some interpretation and interpolation of the data was, of course, necessary in order to make the isopleths continuous over the areas devoid of data.

A Comparison with the Meteor Atlas Charts

A superficial comparison of the new and older charts will give the impression that they are radically different. However, a closer study shows that, except for the addition of new areas and the introduction of numerous irregular lines instead of long smooth curves, there is remarkably little difference in the two sets of charts. In many instances the isotherms and isohalines of the German Charts are a smooth or average representation of the more complicated curves of the new charts. This suggests that the Meteor Charts, although based on far fewer observations, are in fact more nearly correct representations of the average conditions in the North Atlantic than are the new charts. It suggests that the method of drawing the isopleths on the new charts tends to confuse the average picture and the curves should have been smoothed, that is, an averaging process should have been employed in drawing the isopleths. Although it is quite possible that the German Charts

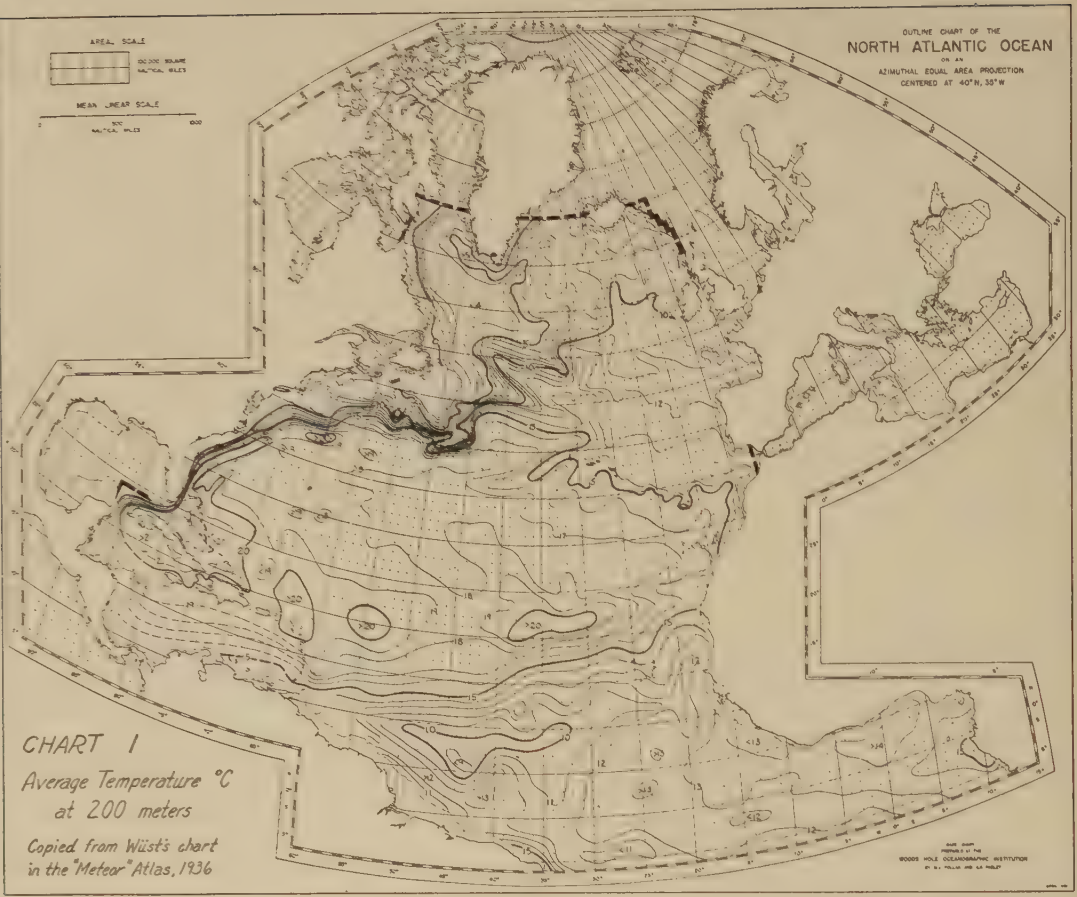
OUTLINE CHART OF THE
NORTH ATLANTIC OCEAN
ON AN
AZIMUTHAL EQUAL AREA PROJECTION
CENTERED AT 40° N, 35° W
AREAL SCALE
MEAN LINEAR SCALE
CHART I
Average Temperature °C
at 200 meters
Copied from Wüst's chart
in the "Meteor" Atlas, 1936
>20
>20
>20
18
15
13
12
10
<13
>14
<12
<11
WOODS HOLE OCEANOGRAPHIC INSTITUTION

Chart 1. Average Temperature (after Wüst).

approximate the true average condition, the new charts have the advantage of showing some of the complexities and details (which may or may not be significant) and of allowing the reader to interpret and smooth the results for himself.

A comparison of these charts brings out the important fact, that over most of the vast extent of the North Atlantic conditions at 200 meters must be very nearly constant. The complex areas on all the charts are confined to certain portions of the ocean and it is evident that in these areas the major ocean currents exist. Most of what follows will be a discussion of the details in these complex areas and, because of the better distribution of temperature data, attention will be focused on the new 200 meter average temperature chart.

The 200 Meter Average Temperature Charts

The new 200 meter temperature chart shows many interesting details not appearing on the German Chart. Since it is almost impossible to discuss these details without referring to currents, the general assumption will be made here that the positions of the major ocean currents coincide with the positions of the pronounced horizontal gradients of temperature at 200 meters. Also, the assumption is made that the current directions are such that the warm water is to the right facing downstream. Because of the fresher water in the following areas the direction of flow is reversed with warm water to the left: in a narrow belt just off the continental shelf from the tail of the Grand Banks northward to Baffin Bay, and similarly from Cape Farewell

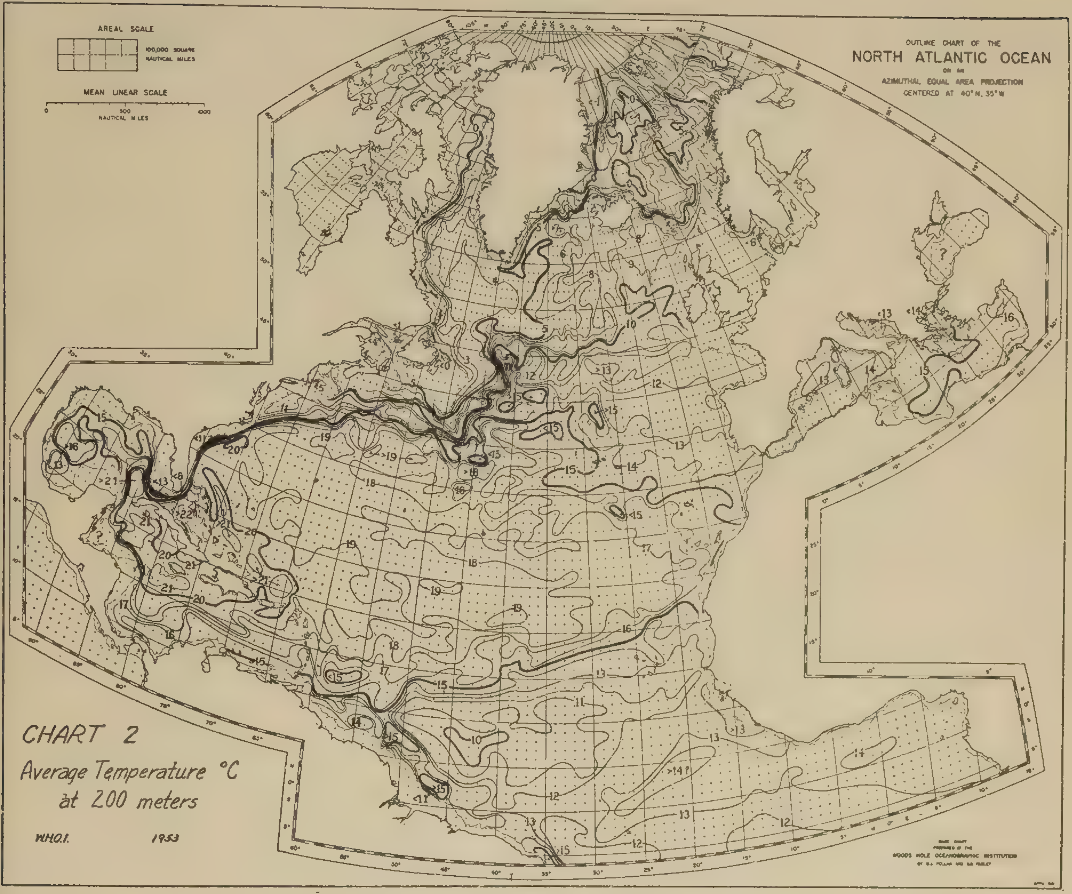
AREAL SCALE
100,000 SQUARE NAUTICAL MILES
MEAN LINEAR SCALE
0
500
1000
NAUTICAL MILES
OUTLINE CHART OF THE
NORTH ATLANTIC OCEAN
ON AN
AZIMUTHAL EQUAL AREA PROJECTION
CENTERED AT 40° N, 35° W
CHART 2
Average Temperature °C
at 200 meters
W.H.O.I.
1953
BASE CHART
PREPARED BY THE
WOODS HOLE OCEANOGRAPHIC INSTITUTION

Chart 2. Average Temperature.

at the southern tip of Greenland northward along the east coast of Greenland to the Polar Sea.

The most pronounced gradient on both temperature charts is the one associated with the Gulf Stream. Between the Florida Straits and the 65th meridian the temperature contrast on the new chart is 2 to 3 degrees centigrade less than on the older chart. In the region between Cape Hatteras and the Grand Banks the zone of maximum temperature, south of the gradient, is displaced further to the south. Both of these changes can be explained in the following manner. If the current is continually shifting its geographical position and we assume the cross-current gradient to be constant then, up to a certain point, an increase in the number of observations averaged in the area will tend to spread out the gradient, decrease the total range of temperature across the gradient, and displace the maximum value to the right, facing downstream. If, as shown in Figure 1, the solid line represents the normal

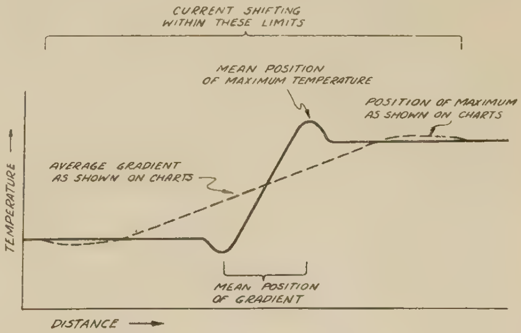
CURRENT SHIFTING WITHIN THESE LIMITS
MEAN POSITION OF MAXIMUM TEMPERATURE
POSITION OF MAXIMUM AS SHOWN ON CHARTS
AVERAGE GRADIENT AS SHOWN ON CHARTS
TEMPERATURE
MEAN POSITION OF GRADIENT
DISTANCE

Fig. 1. Schematic cross-current profile of 200 meter temperature.

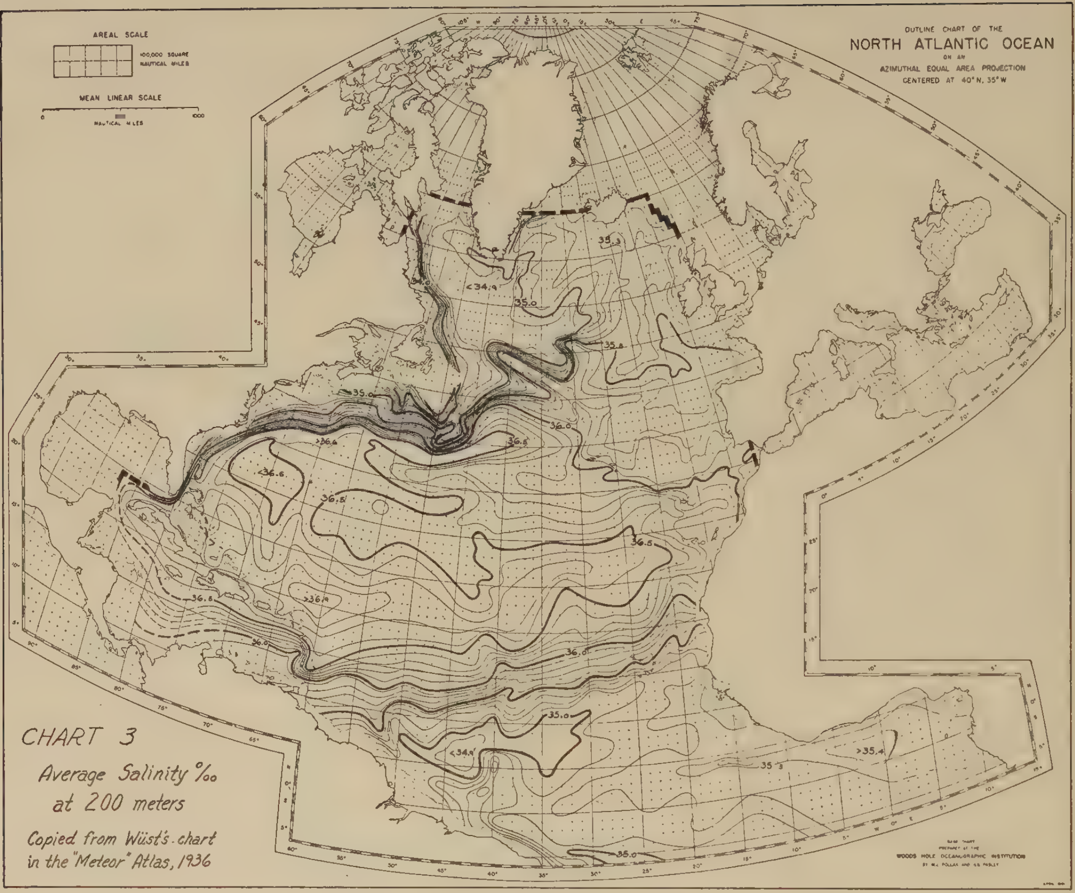
AREAL SCALE
100,000 SQUARE NAUTICAL MILES
MEAN LINEAR SCALE
0
NAUTICAL MILES
1000
OUTLINE CHART OF THE
NORTH ATLANTIC OCEAN
ON AN
AZIMUTHAL EQUAL AREA PROJECTION
CENTERED AT 40° N, 35° W
CHART 3
Average Salinity ‰
at 200 meters
Copied from Wüst's chart
in the "Meteor" Atlas, 1936
35.2
<34.9
35.0
35.0
35.0
36.0
36.5
36.6
36.6
36.8
36.5
36.6
>36.4
36.0
36.0
35.0
<34.9
35.3
>35.4
35.0
WOODS HOLE OCEANOGRAPHIC INSTITUTION

Chart. 3. Average Salinity (after Wüst).

temperature gradient across the current and the current shifts between the limits shown, then the average chart will show the more gradual gradient and the less pronounced maximum and minimum values as represented by the dashed line.

In the area to the south of Nova Scotia and Newfoundland there is what might be termed an intermediate development of the average in the Gulf Stream zone. The single gradient that appears on the German Chart is now broken down into at least two separate gradients. Although this separation of the isotherms appears to support the theory of multiple currents in the area (Fuglister, 1951) it is possible that increasing numbers of observations may again blend the picture and eventually show a single, gradual gradient across the zone. Much of the complicated pattern of isotherms on the new chart, in the Gulf Stream area in particular, but also to some extent in the equatorial regions, may be interpreted as showing the non-continuity or multiple current characteristics of the major ocean currents. This characteristic is not suggested by the German Chart, except perhaps in the area to the east of the Grand Banks, and it may not be indicated again when an average chart based on many more thousands of observations is produced.

The most confused area on the new charts is in the portion of the Gulf Stream System to the east of the Grand Banks. Disregarding the complex details for a moment, it is obvious that the many new observations in this area show that the warm water (> 10° C) flows closer to Flemish Cap and further to the north and west than is indicated on the Meteor

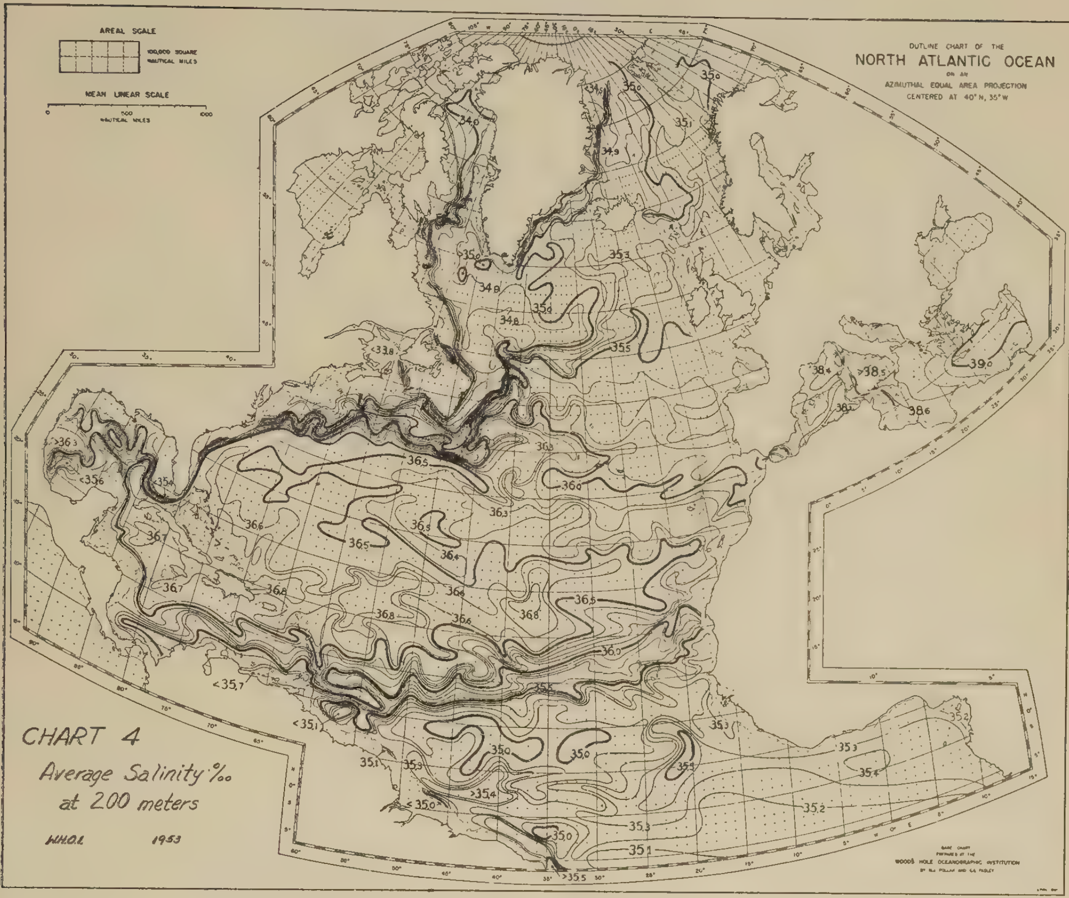
AREAL SCALE
100,000 SQUARE NAUTICAL MILES
MEAN LINEAR SCALE
0
500
1000
NAUTICAL MILES
OUTLINE CHART OF THE
NORTH ATLANTIC OCEAN
ON AN
AZIMUTHAL EQUAL AREA PROJECTION
CENTERED AT 40° N, 35° W
CHART 4
Average Salinity ‰
at 200 meters
W.H.O.I. 1953
34.0
34.5
35.0
35.0
35.1
34.9
35.0
34.8
35.0
34.8
35.3
35.5
<33.8
>36.3
<35.6
<35.4
36.5
36.3
36.0
36.3
36.6
36.7
36.5
36.5
36.4
36.7
36.8
36.6
36.8
36.6
36.8
36.5
36.0
<35.7
35.5
<35.1
35.1
35.3
35.0
35.0
35.3
35.4
>35.4
<35.0
35.3
35.2
35.3
35.4
35.2
35.0
35.3
35.1
>35.5
38.4
>38.5
39.0
38.2
38.6
BASE CHART
PREPARED AT THE
WOODS HOLE OCEANOGRAPHIC INSTITUTION

Chart 4. Average Salinity.

Chart. The pronounced gradient, indicating a northwesterly current, which turns abruptly towards the east near 50° north latitude is one of the most interesting features shown on either chart. One may be tempted to say that it is the bottom topography in this area that is the controlling factor but then it would be necessary to explain how bottom contours at depths of 4,000 meters could affect the course of a current which, according to its density structure, does not extend deeper than 1,500 meters.

To return to the details shown on the new chart in the region to the east of the Grand Banks we see that there are several isolated areas of maximum and minimum temperatures. If this were a truly average picture of the temperature conditions in the area we would interpret these areas as the locations of permanent eddies in the system. A more logical explanation is that this is a region of shifting currents and countercurrents and the distribution of observations is such that the resulting picture is a combination of average and instantaneous values. As we approach the Grand Banks from this area the number of observations increases and the isotherms smooth out.

East of the 30th meridian neither chart defines the area of the Gulf Stream System. The new chart shows a pronounced gradient in the eastern Norwegian Sea but there is no recognizable connection between it and the gradients in the area east of the Grand Banks. If the cross-current gradients decrease in magnitude and the currents shift over wide areas in the northeastern Atlantic then we can expect to find a widespread gradient on the average.

However, as will be shown later, no gradient of as much as 2° C. in a one degree field has ever been observed in the area southeast of the Faeroe-Shetland Channel where the northern branch of the Gulf Stream System presumably flows toward the Norwegian Sea. More will be said on this subject in connection with the discussion of the temperature range and temperature anomaly charts.

In the Norwegian Sea there is a scarcity of data north of the latitude of Jan Mayen (66° N) but in the southern portion, especially in the east, there is an excellent distribution of observations. The most interesting feature is the indicated current area extending northward along the Greenwich Meridian. The Norwegian Current is generally depicted as flowing along the coast of Norway and it is surprising that the chief concentration of gradients lies so far to the west. The pronounced gradient area along the southern boundary of the Norwegian Sea is evidently associated with the ridge that separates the Norwegian Basin from the main body of the North Atlantic. These gradients define a frontal zone and must be associated with relatively permanent currents, but because of the salinity gradients near the Greenland end of the ridge and the generally shoal depths several interpretations of current direction are possible.

In the north equatorial regions the principal differences between the new and the old charts appear in the area near the West Indies and off the coast of South America. The maxima and minima in these areas can be explained in the same way as were those phenomena in the area east of the Grand Banks, that is, the new chart represents a combination of average and synoptic data. As in the Gulf Stream the gradient across the north equatorial current has decreased slightly, the zones of 20° water to the north of the current have disappeared and the area of $< 10°$ water to the south has become smaller.

The Equatorial Countercurrent is only vaguely suggested by the 200 meter temperature distribution except in the western area, around 8° N, 50° W, where a pronounced gradient appears on the new chart. There is no evidence of the existence of the Antilles Current on either the new or the old chart.

In the Mediterranean Sea there are no pronounced gradients of temperature at 200 meters. The positions of the few isotherms on the new chart are somewhat doubtful but it is evident that conditions are relatively uniform with a slight increase in temperature toward the east and south across this sea.

To conclude this discussion of the 200 meter average temperatures, it is evident that a new chart, based on ten times as many observations as were used in the Meteor Atlas, does not alter the general picture as shown by that atlas. Except for a few significant detailed changes the new chart only confirms the average conditions as depicted by Wüst and Defant. The implication that the 200 meter temperature chart may serve as a useful tool in the study of the major ocean currents appears to be sound and, as we have seen, it does raise some interesting and provocative questions.

Range of Observed Temperatures

Chart number 6 shows the range of observed temperatures at a depth of 200 meters in the North Atlantic. These ranges are the maximum minus the minimum observed temperature within each one degree field regardless of the date of the observation. The total range was calculated in order to show where, in the North Atlantic, pronounced horizontal gradients of the temperature at 200 meters have been observed. The assumption is made here that, except for slight seasonal changes, the temperature at 200 meters does not gradually change with time and any marked differences in observed temperatures in a unit field indicate that a pronounced horizontal gradient has existed in the area. Since no averaging process is involved in the production of this chart it should prove useful as a supplement to the average temperature chart in studying the major ocean current of the North Atlantic.

In general the maximum range of temperature occurs in those regions where the average temperature chart shows the maximum horizontal gradients. The highest values occur in the area shown in black off the northeast coast of North America where ranges of from 10° to as high as 16° have been observed. Over most of the ocean the range is less than 2°. Calculations of the seasonal varia-

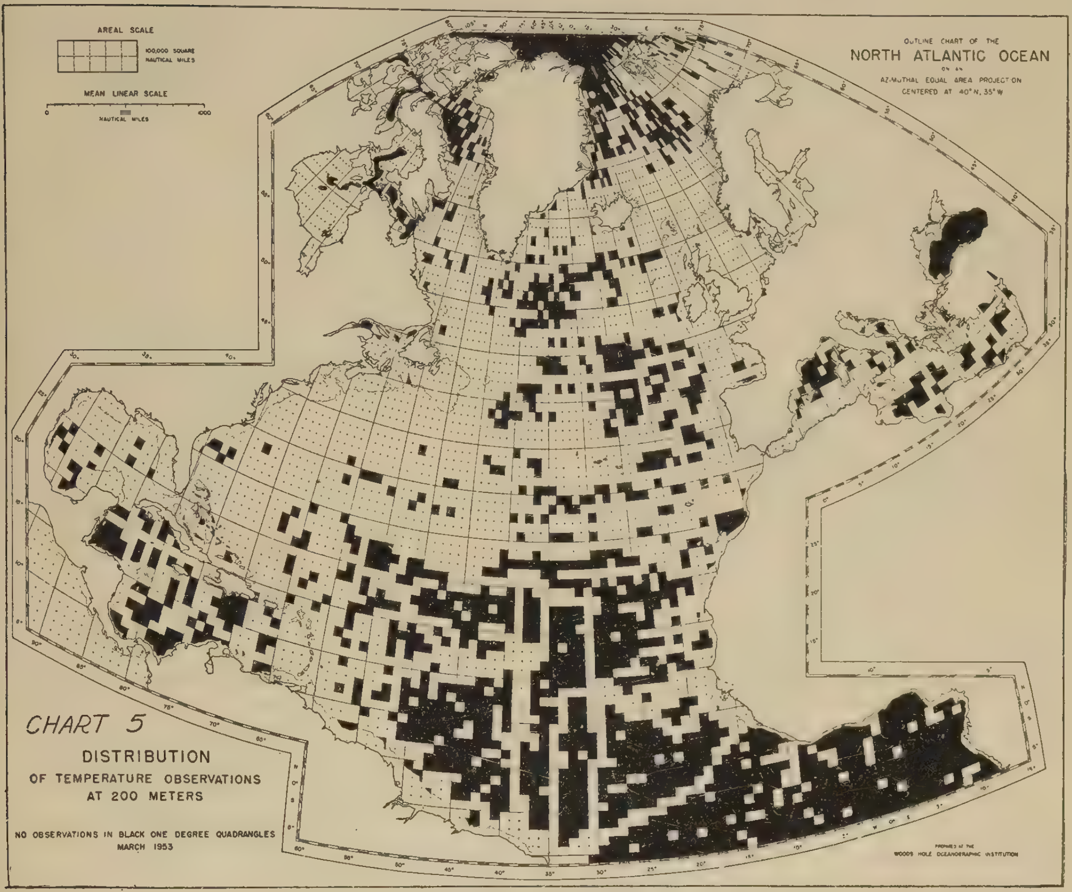
AREAL SCALE
100,000 SQUARE NAUTICAL MILES
MEAN LINEAR SCALE
0
1000
NAUTICAL MILES
OUTLINE CHART OF THE
NORTH ATLANTIC OCEAN
ON AN
AZIMUTHAL EQUAL AREA PROJECTION
CENTERED AT 40° N, 35° W
CHART 5
DISTRIBUTION
OF TEMPERATURE OBSERVATIONS
AT 200 METERS
NO OBSERVATIONS IN BLACK ONE DEGREE QUADRANGLES
MARCH 1953
PREPARED AT THE
WOODS HOLE OCEANOGRAPHIC INSTITUTION

Chart 5. Distribution of Temperature Observations.

tions in the 200 meter temperature, in a few areas where observations are available for all months of the year, indicate that this variation is between 1° and 1.6°. We may assume then that changes in temperature, that we associate with currents, occur in all the areas where the range is greater than 2°. These areas are shaded or black on chart number 6.

The most interesting feature on the range chart is the four prongs of $> 2°$ ranges extending eastward from the Grand Banks area and the fact that the northernmost prong does not extend to the Norwegian Sea. In the area southeast of the Faeroe-Shetland Channel (54° to 61° N. Lat., 9° to 20° W. Long.) there are 402 observations giving range values in 66 of the 77 one degree fields. The seven months from May through November are represented. If a major ocean current exists in this area it is indeed surprising that this number of observations could have been made without once showing a temperature gradient of more than 2° in a unit area.

Unlike the average temperature chart the range chart does indicate the existence of current in the Antilles region. Unfortunately there are too few observations in the eastern equatorial area, in the Caribbean and in the western Norwegian Sea to determine the ranges. It may be argued that the calculation of the total, or maximum, observed range in temperature is too crude a method of study. The range is calculated from only two observations in each unit field and these observations, the maximum and minimum observed temperatures, are the ones most likely to be in error. Of course, every effort has been made to

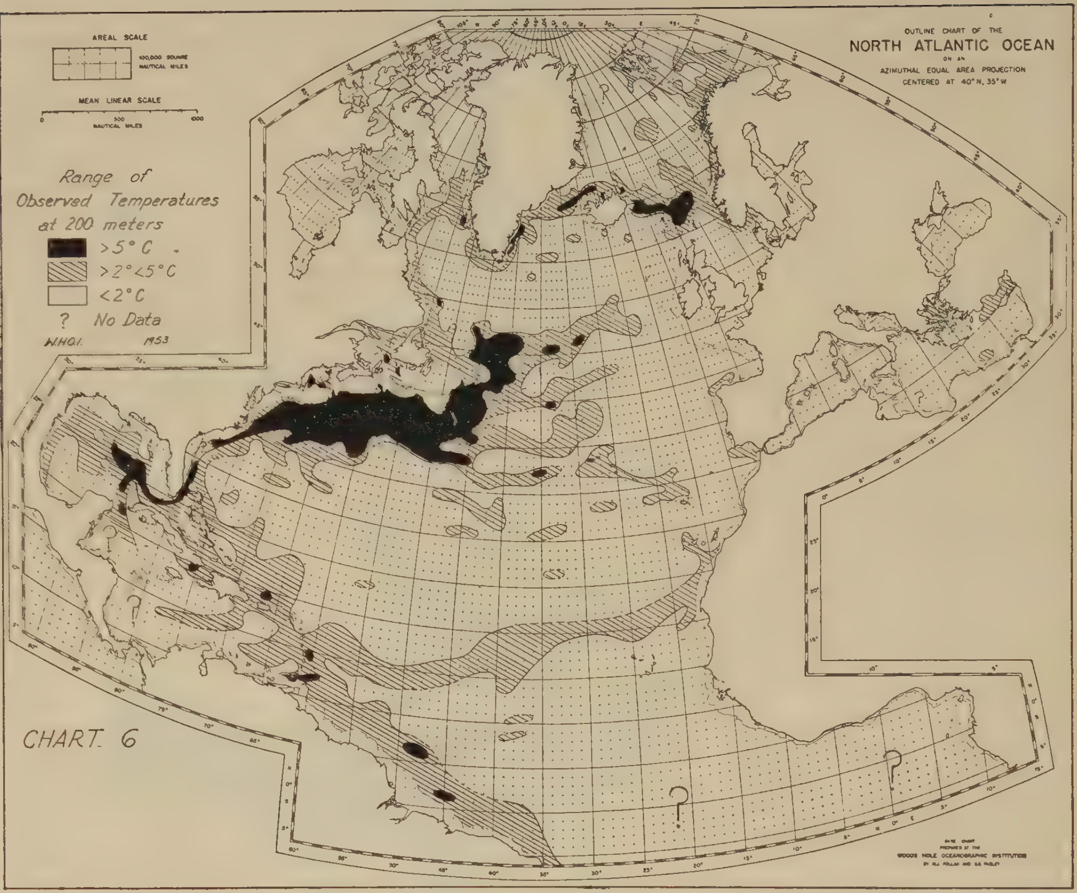
AREAL SCALE
100,000 SQUARE NAUTICAL MILES
MEAN LINEAR SCALE
0
500
1000
NAUTICAL MILES
Range of Observed Temperatures at 200 meters
>5° C
>2°<5°C
<2°C
? No Data
W.H.O.I. 1953
OUTLINE CHART OF THE
NORTH ATLANTIC OCEAN
ON AN
AZIMUTHAL EQUAL AREA PROJECTION
CENTERED AT 40° N, 35° W
CHART 6
BASE CHART
PREPARED AT THE
WOODS HOLE OCEANOGRAPHIC INSTITUTION

Chart 6. Range of Observed Temperatures.

remove from the files any data that could be shown to be in error but, in many cases, no such check was possible. The scarcity of observations in many areas is a more serious drawback than the inclusion of occasional errors. Nevertheless, the range chart produced here achieves a continuity that appears to be reasonable in the light of what is known about the North Atlantic circulation.

Standard Deviation from the Mean Temperature

The standard deviation from the mean temperature could be calculated for each unit area in order to show the probable variation (and to minimize the effect of errors in the extreme values). These calculations were not carried out for the North Atlantic chiefly because of the amount of labor involved but also because the number of observations over large areas did not warrant this approach. The standard deviation was calculated for two areas in the Gulf Stream region in order to compare the results with the average temperature and the range of temperature.

The first area contains the one degree fields that fall on a line between Bermuda and the continental shelf off Long Island. Figure 2 A shows the latitude and longitude of each degree field, the number of observations, the number of months, the average temperatures, the ranges and the standard deviation. The average temperature curve shows that the maximum gradient (the Gulf Stream) lies between the unit fields whose centers are at 37° 30′ and 38° 30′ north latitude; the standard deviation is highest in the unit field

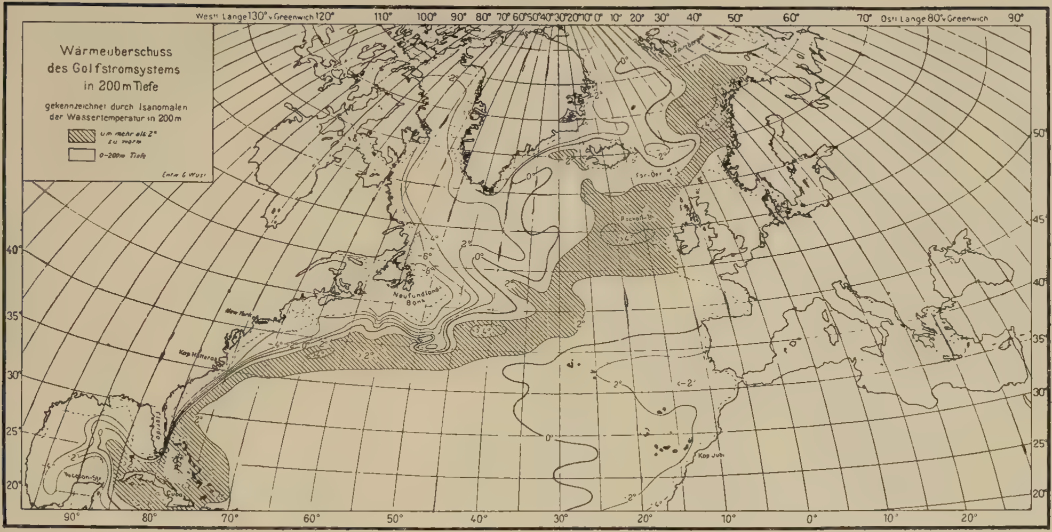
Wärmeuberschuss
des Golfstromsystems
in 200 m Tiefe
gekennzeichnet durch Isanomalen
der Wassertemperatur in 200 m
um mehr als 2° zu warm
0–200m Tiefe
Entw. G. Wüst
West. Lange 130° v. Greenwich 120°
Ost. Lange 80° v. Greenwich
Neufundland-Bank
New York
Kap Hatteras
Florida
Kap Juby
Färöer
Rockall-B.

Chart 7. Temperature Anomalies (after Wüst)

centered at 37° 30′ N and the high ranges are spread over three unit fields from 36° to 39° north latitude. We can interpret the standard deviation curve as showing that there is one major current in the area and that its mean position is at about 37° 30′ N. The range curve can be interpreted as showing that the major current in this area varies in position between 36° and 39° north latitude.

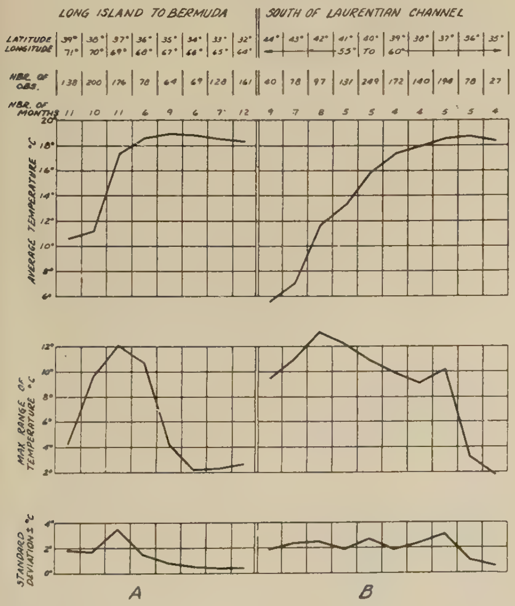

Fig. 2. 200 meter profiles across the Gulf Stream region.

In the second example shown in Figure 2 B the unit fields were enlarged to include five degrees of longitude. The area extends from the continental shelf south to 35° N crossing the Gulf Stream between 55° and 60° west longitude. The average temperature curve shows the maximum gradient between 40° and 44° N. The standard deviation is highest at 37° 30′ N with secondary maxima at 40° 30′ N and 42° 30′ N. The high ranges are spread over eight unit fields from 37° to 45° N. The average temperature curve indicates that the Gulf Stream has become wider in this zone, with perhaps two branches both north of 40° north latitude. The range and the standard deviation curves both show high values for all the area north of 37° north latitude. The standard deviation curve may be interpreted as showing three zones of maximum gradients.

Temperature Anomalies

In order to show the continuity of the Gulf Stream and the Norwegian Current, Wüst (1937) calculated the zonal mean temperatures at a depth of 200 meters for each 2½° of latitude from 20° to 75° north latitude in the North Atlantic. From these mean temperatures he calculated the anomalies. He considered that the areas showing a positive anomaly of greater than 2° defined the position of the Gulf Stream System. The chart that Wüst published is reproduced here as Chart 7.

On the bases of the 40,000 observations now available the zonal mean temperature for each one degree of latitude was calculated. These values are plotted in Figure 3, the values obtained by Wüst are shown on the diagram by × marks and it can be seen that there is a surprising agreement in the two sets of zonal averages.

The temperature anomalies as calculated from the zonal averages (for every 2° temperature difference) are shown on Chart 8. Here it is apparent that the new chart differs from Wüst's in several respects and this in spite of the fact that the zonal averages used were virtually the same. In the Gulf Stream area south of 40° north latitude the changes appearing on the new chart may be attributed to the effects of averaging. This was discussed on page 49 where it was pointed out that when averaging many observations in an area of a shifting current the zone of maximum temperature is displaced to the right — facing downstream — and the maximum temperature values are decreased. This may account for the break in the shaded zone (> 2° positive anomalies) off Florida and the very nearly broken segment south of the Grand Banks. To the east of the Grand Banks the shaded zone is much more extensive on the new chart. This is due to the fact that at the time when Wüst made his chart there were very few observations in the region between 35° and 45° west longitude and 40° and 50° north latitude and the new data show that warm currents exist in the northern portion of this area.

In connection with the discussion of the continuity of the Gulf Stream System in the northeastern Atlantic, the difference between the two anomaly charts in the area southeast of Iceland is of particular interest. Wüst's chart shows a pronounced flow of warm water into the Norwegian Sea, through the Faeroe-Shetland Channel, with only a suggestion of a branch of warm water pointed toward the west of Iceland. The new chart reverses this picture, most of the warm water is concentrated to the south and west of Iceland with only a suggestion of flow into the Norwegian Sea along the European continental shelf. This difference in the two charts may be interpreted in various ways, as in fact the entire subject of temperature anomalies may be, but taken together with the evidence of the average temperature chart and the range chart it does suggest that the high positive anomalies in the eastern Norwegian Sea are not entirely the result of a flow through the Faeroe-Shetland Channel. It is interesting to speculate on what these anomalies would be if the Norwegian Sea was entirely disconnected from the Atlantic.

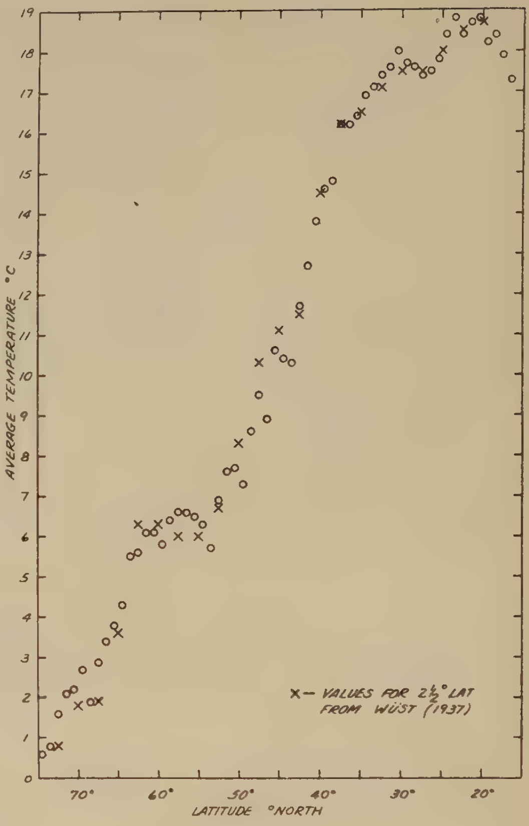

Fig. 3. Average temperatures at a depth of 200 meters for each degree of latitude for the North Atlantic Ocean.

The 200 Meter Salinity Charts

Although the new salinity chart (Chart 4) is based on far fewer observations than the new temperature chart the same trend of differences from the Meteor Atlas Chart (Chart 3) is evident. Virtually all the statements made concerning the new average temperature chart can be applied to the new salinity chart.

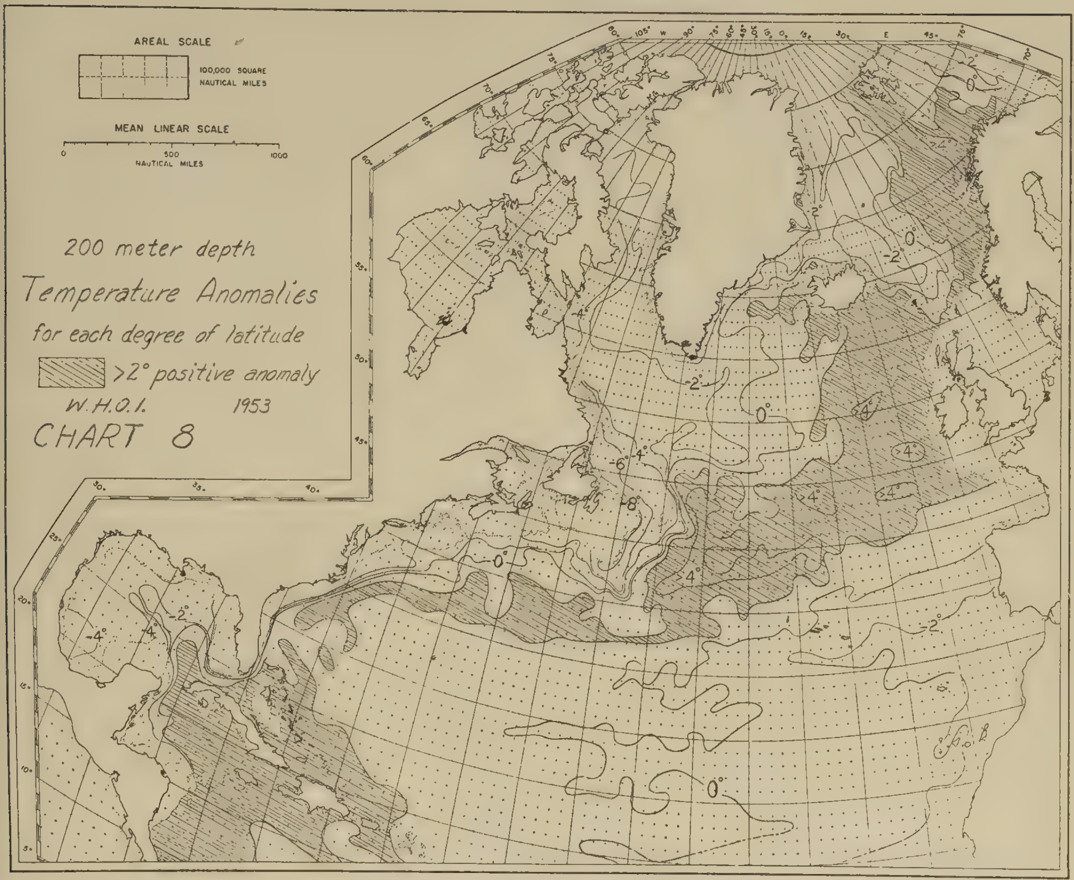
AREAL SCALE
100,000 SQUARE NAUTICAL MILES
MEAN LINEAR SCALE
0
500
1000
NAUTICAL MILES
200 meter depth
Temperature Anomalies
for each degree of latitude
>2° positive anomaly
W.H.O.I. 1953
CHART 8
-2°
0°
4°
-4°
-6°
-8°
2°

Chart 8. Temperature Anomalies.

However, no attempt has been made here to correlate the new temperature and salinity charts; each chart was drawn independently even though there were many areas where no salinity data were available and the placement of the isotherms. may have been used to determine the position of the isohalines.

Conclusions

It is quite apparent from the foregoing that, far from being obsolete, the charts in the Meteor Atlas that deal with conditions at a depth of 200 meters in the North Atlantic are still to be considered as accurate representations of the mean state. This atlas shows, as we might expect, a certain continuity of conditions with increasing depth and, therefore, we may assume that all the charts in this atlas are equally reliable. The major drawback of the Meteor Atlas is that it does not cover the Norwegian Sea, the Gulf of Mexico, the Mediterranean Sea and Baffin Bay.

The new set of charts presented with this paper show that, although much can be learned from studying the average conditions as depicted in the Meteor Atlas, if we wish to study the major ocean current systems the average picture is somewhat misleading. The value of charts showing the mean state can be greatly increased if they are supplemented by charts showing the range of conditions and the standard deviations from the mean. However, it is obvious that it will be many years before enough observations are obtained to do this for any depths greater than 200 meters. Even at this depth the distribution of observations over the North Atlantic is too uneven to make such charts completely reliable.

It may seem a paradox but the chief value of the new 200 meter average temperature chart, aside from the fact that it covers a more extensive area in the North Atlantic than the Meteor Atlas, is the fact that it does not represent a true average picture. Because of the uneven distribution of data and the non-averaging system of drawing the isotherms this chart focuses the attention on many details that would not exist on a chart more truly representative of the average. This is especially evident in the major ocean current areas.

Several interesting questions are posed if the new 200 meter temperature chart, supplemented by the range chart, is used as a current chart. Why does the Gulf Stream break down into more than one current long before it reaches the longitude of the Grand Banks and why does the system break down so much more rapidly into at least four currents after it has passed this longitude? Why is there no pronounced current extending from this system in mid-Atlantic to the Norwegian Sea and is the circulation in that sea largely self-contained? Why is the Antilles Current only vaguely suggested on the range chart and not at all on the average temperature chart? How far does the current that passes through the Yucatan Channel penetrate into the Gulf of Mexico before turning about to flow out through the Straits of Florida? Why is there so little evidence of an anticyclonic current system over the main body of the North Atlantic?

No attempt is made here to answer these questions. It has been assumed that a cross-current temperature gradient at a depth of 200 meters exists wherever there is a major ocean current. If this assumption is wrong then the above questions are meaningless. But if it is a justified assumption then these questions are valid and should be of considerable interest.

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ESSELTE, STHLM 54

Contribution No. 671

Deep-Sea Research, 1954, Vol. 1, pp. 141 to 169. Pergamon Press Ltd., London.

Notes on the Peruvian coastal current. 1. An introduction to the ecology of Pisco Bay[1]

MARY SEARS

Summary—Biological calamities of the Peruvian Coastal Current have long been associated with undue warming of the surface water. These high water temperatures have most frequently been attributed to an incursion of fresher water from the north (" El Niño "). More recently they have also been ascribed to the intrusion of wedges of saltier, warm offshore water and even to the discharge from local streams. Re-examination of the warming processes in Pisco Bay indicates that solar radiation probably accounts for a large proportion of the high temperatures observed there. Such warming can occur whenever upwelling, the only effective source of cooling, ceases for any appreciable period.

From available evidence, there appears to be an annual temperature range of about 7°C. Salinities of the current as a whole do not normally vary by as much as 2‰ whether the water be derived from upwelling, from offshore or from " El Niño." The ranges of these characteristics are much more limited than in some coastal waters and about the same as for others. The actual temperature limits are very nearly the same as for the cycle in the Mediterranean.

Consequently, before the relationship between temperature and the recurrent biological disasters can be understood, it is suggested that two peculiarities of the area should be studied in detail: (1) the process of upwelling which provides nutrient salts for the growth of phytoplankton and (2) the effect, if any, of that fraction of the birds' excreta dropped in the water on the nutrient cycle and on the character of the phytoplankton.

INTRODUCTION

THE economic importance and abundance of the guano-producing birds have long focused attention on the peculiarly rich environment provided by the inshore waters of the Peruvian Coastal Current. Despite this, remarkably little is known of the seasonal or annual cycle of events which support such enormous populations there, because previous studies have been mostly incidental to other work. Thus, there are a few widely-spaced oceanographic stations forming part of more extensive surveys elsewhere[2] and surface observations from vessels traversing the area.[3] Time and facilities precluded detailed hydrographic and biological surveys from most fisheries programmes.[4]

More spectacular and more disturbing to the economy, however, are the recurrent periods when the water temperatures rise suddenly and the birds die of starvation by the thousands. Such events have most often been attributed to the encroachment of warm water from the north (" El Niño "). This is accompanied by torrential rains and northerly rather than southerly winds in northern Peru (MURPHY, 1936; SCHOTT, 1931; ZORELL, 1928). In the Pisco area, on the other hand, there is shift in the winds from southeast to southwest (VOGT, 1942). During such periods, the anchovies are likely to disappear and the guano birds then desert their nests in search of food. Some die of starvation and others migrate to Chile. " Red water " is also frequently reported as a consequence of " El Niño." This may cause an acrid stench (cf., BRONGERSMA-SANDERS, 1948; WOODCOCK, 1948). Fish and large invertebrates subsequently die or are found in a moribund condition on the beaches. These " crash " periods have come to be expected at intervals of seven years (i.e., 1911, 1918, 1925, 1932, 1939 and 1941): some (1891, 1925, 1953) have been more severe than others. Various phases of these catastrophies have been described,[5] but there are few published data, other than surface temperatures. In many instances, these do not sufficiently identify the source of a given water mass.

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[1] Contribution No. 671 of the Woods Hole Oceanographic Institution.

[2] AGASSIZ, 1906; Discovery Committee, 1949; FLEMING, *et al.*, 1945; FUNDER, 1916; GUNTHER, 1936, 1936a; SVERDRUP, 1930, 1931; Scripps Institution of Oceanography, 1952; WOOSTER, 1952.

[3] COKER, 1918; Deutschen Seewarte, 1930; MURPHY, 1923, 1925, 1926, 1936; SCHOTT, 1931, 1932, 1952; SCHWEIGGER, 1942, 1942a, 1943, 1947, 1949, 1951, 1953; ZORELL, 1928.

[4] BINI, 1952; COKER, 1908, 1908a, 1908b, 1908c; FIEDLER, JARVIS and LOBELL, 1943; LANDA, 1953; ROJAS, 1953.

During studies of the guano-producing birds in Peru (VOGT, 1942), it was evident that the birds' lives were so dependent on sea conditions, especially on the abundance of anchovies, that a preliminary oceanographic and biological survey of Pisco Bay was made during the latter part of 1941. Surface and subsurface temperatures were observed at weekly intervals over an area of roughly 400 square miles (Fig. 1). Water samples for salinity determinations[6] were obtained, if possible, when occupying a station for the first time. These were the first subsurface observations in the littoral zone off the coast of Peru to be taken at close intervals in time and space and also under more or less " normal " conditions.

On two occasions, temperature and salinity data, as well as plankton samples were collected to the north and offshore west of Chincha Norte for a distance of about 125 miles for comparison with earlier observations (Footnote 3). Temperatures were also recorded and phytoplankton samples gathered each morning in the immediate vicinity of Chincha Norte. In addition, anchovies were brought out to the island several days each week by local fishermen.

The survey in Pisco Bay was supplemented by a similar one in the waters off Cabo Blanco in January 1942.

STATEMENT OF THE PROBLEM

Anchovies are the chief food of the guano-producing birds and disappearance of the fish means starvation for the birds (VOGT, 1942). Consequently, it is important to learn the circumstances under which the fish vanish from the surface of the Peruvian coastal waters. Two hypotheses as to where the fish disappear during the " crash " years have been proposed and both assume that high temperatures are directly responsible. One is that the anchovies migrate southward (VOGT, 1942) and this is in keeping with the idea that the " crash " years result from an unusual invasion of warm water (" El Niño ") from the north. The other (DEL SOLAR, 1942) suggests that the schools of anchovies move offshore into cool deep water. This suggestion is based on the fact that the tunas which invade the coastal areas at such times have preyed upon anchovies. There is little or no precise evidence to prove the validity of either proposal.

Some (SCHWEIGGER, 1943, p. 37) believe that the Peruvian anchovy feeds primarily on copepods and that they therefore follow the latter[7] into deeper water during

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[5] CURRIE, 1953a; JAMES, 1953; RAHM, 1937; SHEPPARD, 1931; STIGLICH, 1925; WILSON-BARKER, 1931, in addition to those cited in the text above.

[6] Salinity titrations were carried out by members of the technical staff at the Woods Hole Oceanographic Institution. Because the method is not reliable, the salinities determined by hydrometer readings are not included in the discussion.

[7] CLARKE, 1933, 1934, 1934a; GARDINER, 1933; HANSEN, 1951; JOHNSON, 1942; NICHOLLS, 1934; ROSE, 1925; RUSSELL, 1925, 1926, 1927, 1927a, 1928, 1928a.

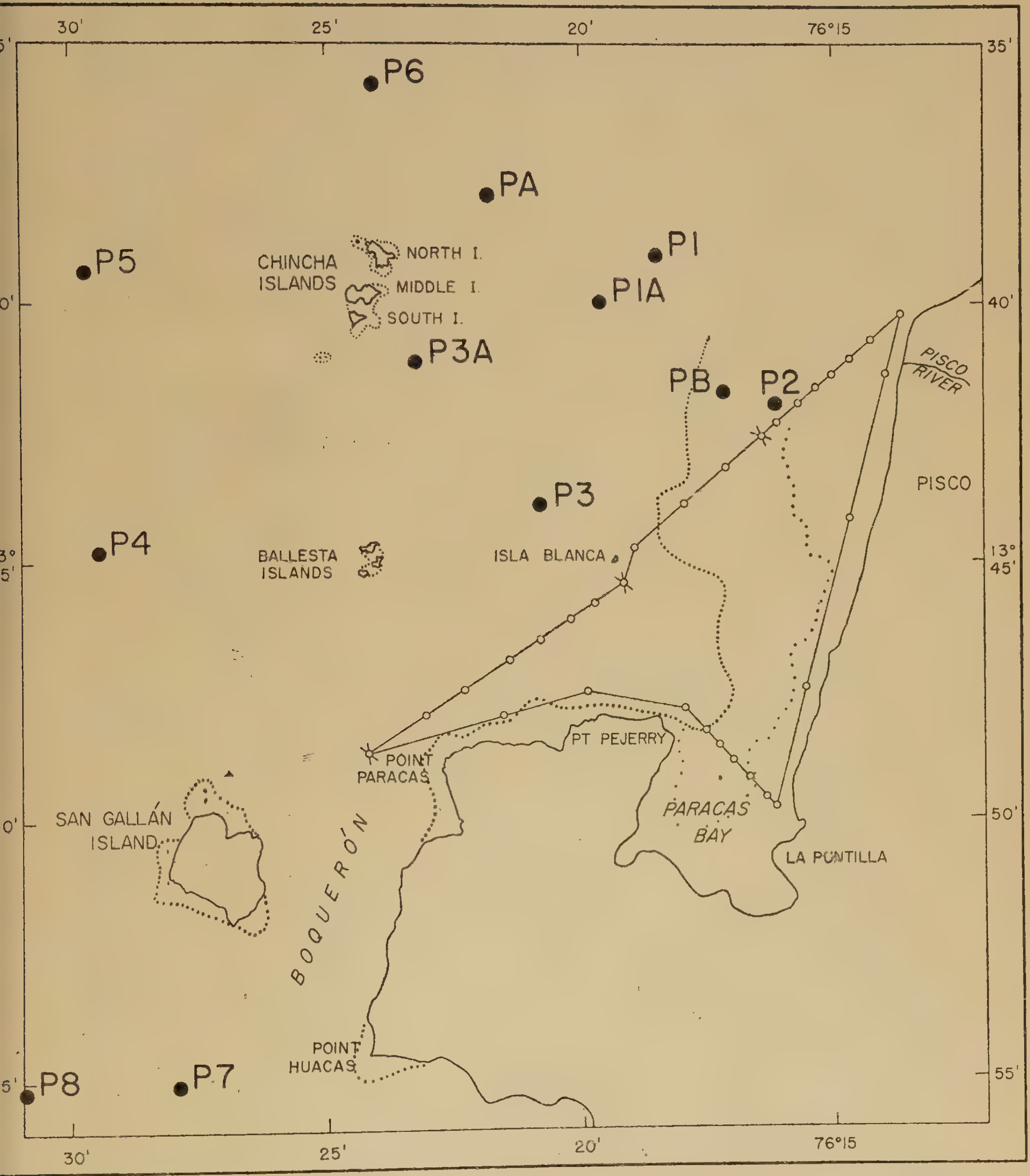
30'
25'
20'
76°15
35'
40'
13° 45'
50'
55'
P6
PA
P5
CHINCHA ISLANDS
NORTH I.
MIDDLE I.
SOUTH I.
P1
P1A
P3A
PB
P2
PISCO RIVER
PISCO
P3
P4
BALLESTA ISLANDS
ISLA BLANCA
PT PEJERRY
POINT PARACAS
PARACAS BAY
LA PUNTILLA
SAN GALLÁN ISLAND
BOQUERÓN
POINT HUACAS
P8
P7

Fig. 1. Place-name chart of Pisco Bay and vicinity showing position of stations listed in Table 2, Section A. The ositions of the stations in Fig. 4 are also plotted and those with the symbol ¤ indicate stations where subsurface temperatures were taken at 10 and 20 metres.

the day. There are a few observations which seem to indicate that such a diurnal migration of anchovies may take place when the water is warmer than 20°C (HUTCHINSON, 1950). However, other than these records such evidence as we have indicates that this is not usually the case. During the " El Niño " period of 1953, schools of anchovies were reported at the surface in the general vicinity of Lobos de Afuera in northern Peru in water temperatures of 24°C to 25°C (SCHWEIGGER, 1953). Furthermore, VOGT, (1942) points out that were such diurnal migrations responsible for the disappearance of the anchovies, they would return to the surface at night. In this event, it is probable that the pelicans, which are known to feed at night, if need be, would prey upon the anchovies then. This does not apparently happen during catastrophic periods, because the pelicans, like the cormorants and boobies, die of starvation. Also, were the anchovies preying primarily upon copepods one might suppose that this sort of migration would occur during " good " times as well. Normally, however, the anchovies are sufficiently abundant at the surface to meet the food requirements of the birds (HUTCHINSON, 1950).

Other species of anchovy are reported to feed on phytoplankton at least for portions of the year[8] and there is considerable evidence that the Peruvian anchovy does likewise. The presence of diatom frustules of some of the more resistant species, such as are found in the bottom mud (NEAVERSON, 1934), have been recorded in guano deposits, both ancient and modern (CANCINO, 1950; MURPHY, 1936, p. 97; personal observations). This would appear to indicate that diatoms were present in the digestive tract of fish which the birds had eaten. Furthermore, VOGT (1942) noted that the periods when the food supply of the cormorants appeared to be plentiful, as reported by the wardens, corresponded in general with periods when the water was least transparent (i.e., the phytoplankton was so abundant as to make the water murky). Examination of the stomach contents of more than 2,000 individuals indicate that the Peruvian anchovy does feed primarily on phytoplankton, especially diatoms, at least over a period of months (29 September to 19 December 1941). More recently, similar results have been obtained which extend the period from June through January and February (ROJAS, 1953).

The production of diatoms in sufficient numbers to provide for the guano birds and other predators is in large part determined by the supply of nutrient salts. These are not likely to be a limiting factor under usual conditions because the cool coastal waters which result from upwelling[9] keep their concentration high in the photic zone (GUNTHER, 1936). Therefore events in the sea which might interrupt or disrupt this cycle could account for the recurrent disasters in " crash " years.

Biological calamities of the Peruvian coast have always been associated with undue warming of the water. These high temperatures have most frequently been arttibuted to an incursion of fresher water from the north (" El Niño "). At times, however, they have been ascribed to wedges of saltier, warm offshore water approaching the coast (GUNTHER, 1936; SCHWEIGGER, 1942, pp. 71-73; VOGT, 1942) and sometimes to the effluent from local rivers such as that from the Pisco and San Juan de Chincha Rivers (SCHWEIGGER, 1942, pp. 77-80). It has also been suggested that solar radiation may be significant in local warming (SCHWEIGGER, 1942, p. 77). Whether the effect of high temperatures be a direct one or an indirect one due to differences in the concentration of nutrient salts of the water masses concerned, the reasons for such temperature increases are important in understanding the ecological relationships of the Peruvian coastal waters. Consequently, an attempt is made here to distinguish the relative importance of the several types of warming.

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[8] There are a number of papers (ANDREU y RODRÍGUEZ-RODA, 1951; DEBUEN, 1931; FAGE, 1911, 1920; MIRANDA y RIVERA, 1930) which provide background information on feeding, migrations, etc., for the Mediterranean anchovy.

[9] GUNTHER, 1936; SCHOTT, 1931, 1932; SVERDRUP, 1930, 1931. Also, cf., CURRIE, 1953, for the Benguela Current and SVERDRUP and FLEMING, 1941, and California, Marine Research Committee, 1953, for the California coast.

WARMING IN PISCO BAY

Warm temperatures due to an incursion of " El Niño " are said to extend at times as far south as Pisco Bay. In 1925, there were a sufficient number of surface temperatures recorded from vessels traversing the waters of the Peruvian coast to document a progressive southward advance of temperature increases as far south as Pisco Bay (SCHOTT, 1931, pp. 211-212; MURPHY, 1926; ZORELL, 1928). These persisted in Pisco Bay from 15 to 24 March. Subsequently, it has been learned that surface temperatures as high as 20°C to 22°C are common in the Bay and even as high as 24°C to 25°C are not infrequent in February, March and possibly even in April. These temperatures are not considered to have resulted from an incursion of " El Niño " (SCHWEIGGER, 1942; VOGT, 1942). More recently (1953), when " El Niño " extended only as far south as Paita, warming *in situ* took place to the south apparently due to a cessation of upwelling (AVILA, 1953). Since this was the worst " El Niño " year since 1925, the possibility is raised that a similar situation existed in 1925 and that " El Niño " was not responsible for the temperature increase in Pisco Bay that year.

To verify the characteristics of " El Niño " water, simultaneous observations of temperature and salinity at several subsurface depths were made off Cabo Blanco (4°16′ S, 81°15′ W) in January 1942, the season when " El Niño " might be expected there. The resulting T-S diagram (Fig. 2) indicates that in the upper 25 metres, the temperatures were as high (21°C to 23°C) or a little higher than off Pisco, but the salinities were consistently lower than might be expected for these temperatures in the Pisco Bay area (Fig. 2; cf., Tables 1 and 2). The layer of fresher water was 3 to 10 metres deep within about 1·5 miles from the beach and 25 metres deep at about 30 miles offshore. Below 50 metres, the water had essentially the same characteristics as in the vicinity of Pisco Bay. At intermediate depths, the water appeared to be a mixture of the two.

Fresher water similar to that found off Cabo Blanco in January 1942 (Fig. 2) was found extending northward from Lobitos in September 1927 and November 1929 (Deutschen Seewarte, 1930), to the north and west in July and August 1931 (DISCOVERY COMMITTEE, 1949, Sta. Nos. 708-712, 715-719), and also as far south as 8°51′ S, 79°31′ W in March 1931 (SCHOTT, 1931, p. 245). The latter, it should be noted, was farther south than in 1953 and yet there is no mention in the scientific literature, insofar as I am aware, to indicate that 1931 was a " crash " year. Water of this sort was not found in the Pisco area during the latter part of 1941 or in 1953 (AVILA, 1953; POSNER, 1953).[10] Thus, at times, situations off the Peruvian coast, formerly attributed to " El Niño " are not of this origin as already recognised by GUNTHER (1936), SCHWEIGGER (1942), and VOGT (1942).

[10] SCHWEIGGER (1953) has entered some salinity data on charts, but without giving the temperatures taken at the same time. Insofar as one can judge by interpolation of the temperatures, the salinity values given on Map Nos. 3, 4 and 5 appear to be in agreement with other reports. Those on Map Nos. 1 and 2 appear to indicate that " El Niño " water was present.

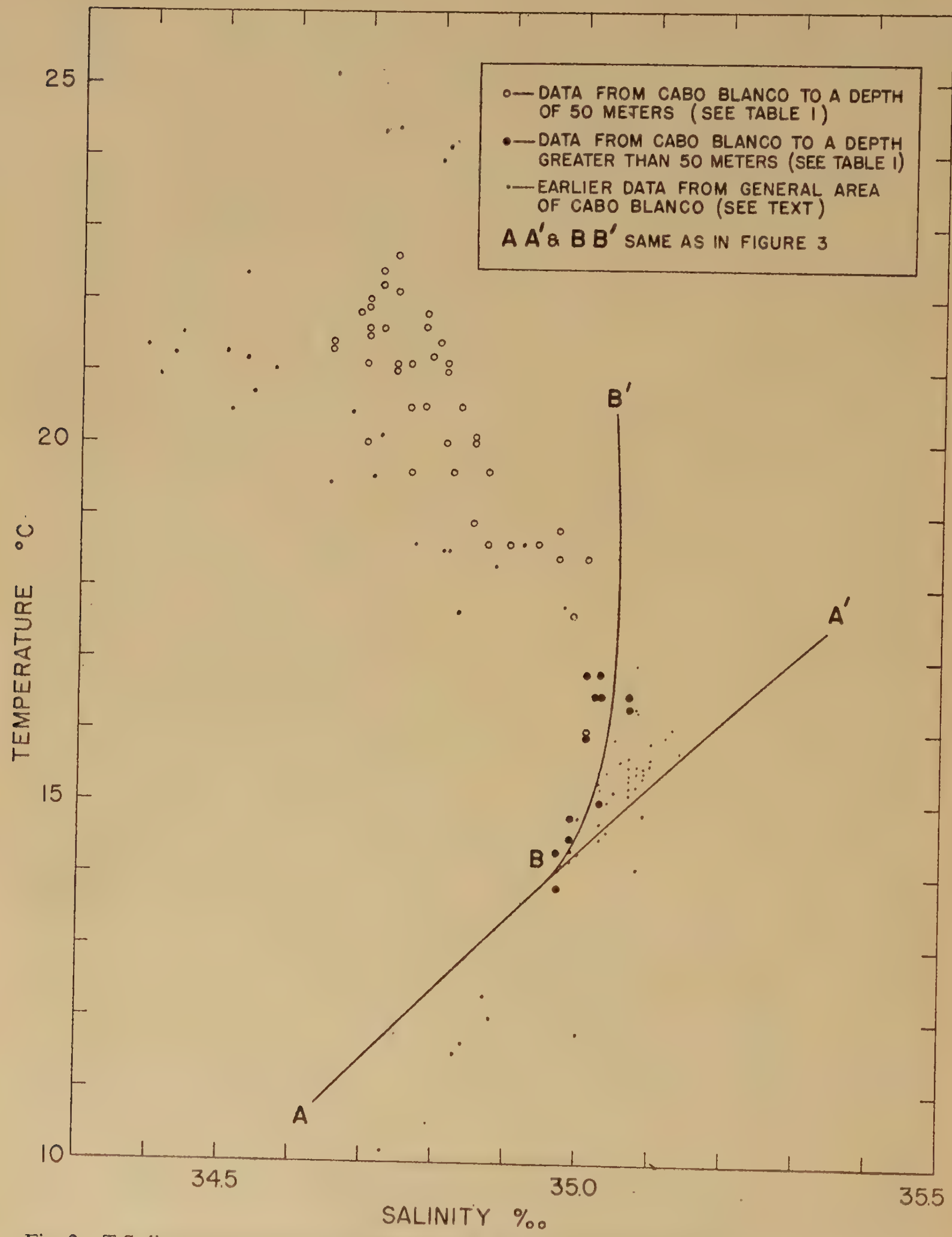


Fig. 2. T-S diagram comparing characteristics of the water in the Cabo Blanco area with earlier records of similar origin.

Intrusions of tongues of warm offshore water, first mentioned by GUNTHER (1936) have been considered as a source of higher temperatures in Pisco Bay (GUNTHER, 1936, p. 194; SCHWEIGGER, 1942, pp. 71-73; VOGT, 1942) but these observations were not accompanied by salinity determinations to prove their offshore origin. To ascertain whether offshore water has been found in the general vicinity of Pisco Bay, the available temperature and salinity data from pertinent depths out to 85° W, and from 5°S to 17°S were plotted on a conventional T-S diagram[11] for comparison with those from the *Carnegie* in the same latitudes, between 90°W and 115°W (*Carnegie* Sta. Nos. 46, 47, 75, 76, 77, 78, 79). The latter are situated where a maximum salinity obtains (Fig. 3, AA′) and may be considered as characteristic of the water masses from the Eastern South Pacific as a whole.[12] The great majority of the points fall within relatively narrow limits for depths greater than 200 metres (Fig. 3), but at lesser depths there is a marked scattering at most stations between the Peruvian coast and 95°W. The scatter is accentuated when curves are plotted for individual stations. These curves, because of the uniformity in salinity in the upper layers, are indicative of upwelling (as will be mentioned again in another connection). Both presentations indicate that the water is distinctly fresher and usually somewhat cooler in the shallower layers than is characteristic for the Eastern South Pacific as a whole (Fig. 3, AA′). These data suggest, then, that the relatively warm saline water characteristic of the Eastern South Pacific does not ordinarily occur within several hundred miles of the South American coast. The *William Scoresby* observations for depths down to between 30 and 50 metres at Sta. Nos. 667, 668, 670, 671, 674, 682, 683, 686, 730, 731 and 734, as well as those taken from the *Oldenberg* (DEUTSCHEN SEEWARTE, 1930) at the surface west of 80°W in the sector under consideration are the exceptions. The data from the shallow depths at these stations fall close to AA′ on the T-S diagram (Fig. 3), indicating an offshore origin. Only three, however, are on the continental shelf and none are within about twenty miles of shore. Although such water was found about 112 miles to the westward at the time of our observations, it was not found in the Pisco Bay area. It therefore remains to be learned whether warm offshore water with salinities higher than about 35·3‰ ever significantly affects the Pisco area.[13]

Within Pisco Bay proper (Fig. 3), all temperatures and salinity data when plotted on a T-S diagram (Table 2; FUNDER, 1916) fall along BB′, almost at right angles to the abscissa. The salinity does not vary by more than about 0·15‰ between the greatest subsurface depth on the continental shelf and the surface even although the temperatures vary from 13·8°C to 20·0°C, the extremes found in the area at the time of our observations. Water of 13°C to 14°C, the minimal recorded in the Bay, is usually found with salinities of 34·96‰ to 35·06‰ at depths of 150 to 200 metres, perhaps a little deeper (250-300 metres) at stations off the continental shelf

[11] Such a wide latitudinal span was included because so few observations have been made within the immediate offing of Pisco Bay. Since the scatter at shallower depths was as marked when only the few data between 12°S and 14°S were used, it does not appear that for purposes of the present analysis any undue inconsistencies were introduced.

[12] There seems to be some precedent for such a procedure (REDFIELD, 1950; SVERDRUP, JOHNSON and FLEMING, 1942, Fig. 194; FLEMING, *et al.*, 1945, Figs. 205, Sta. Nos. 78-89; SVERDRUP, *et al.*, 1944, pp. 126-127, Fig. 14).

[13] SCHWEIGGER (1947, p. 60) reports salinities of 35·25‰ but corresponding temperatures and localities are not given. Although this value is relatively high for recently upwelled water, it has been recorded at temperatures between 13° and 14°C. It therefore is not possible to determine the source of a water mass with such salinity values without more data.

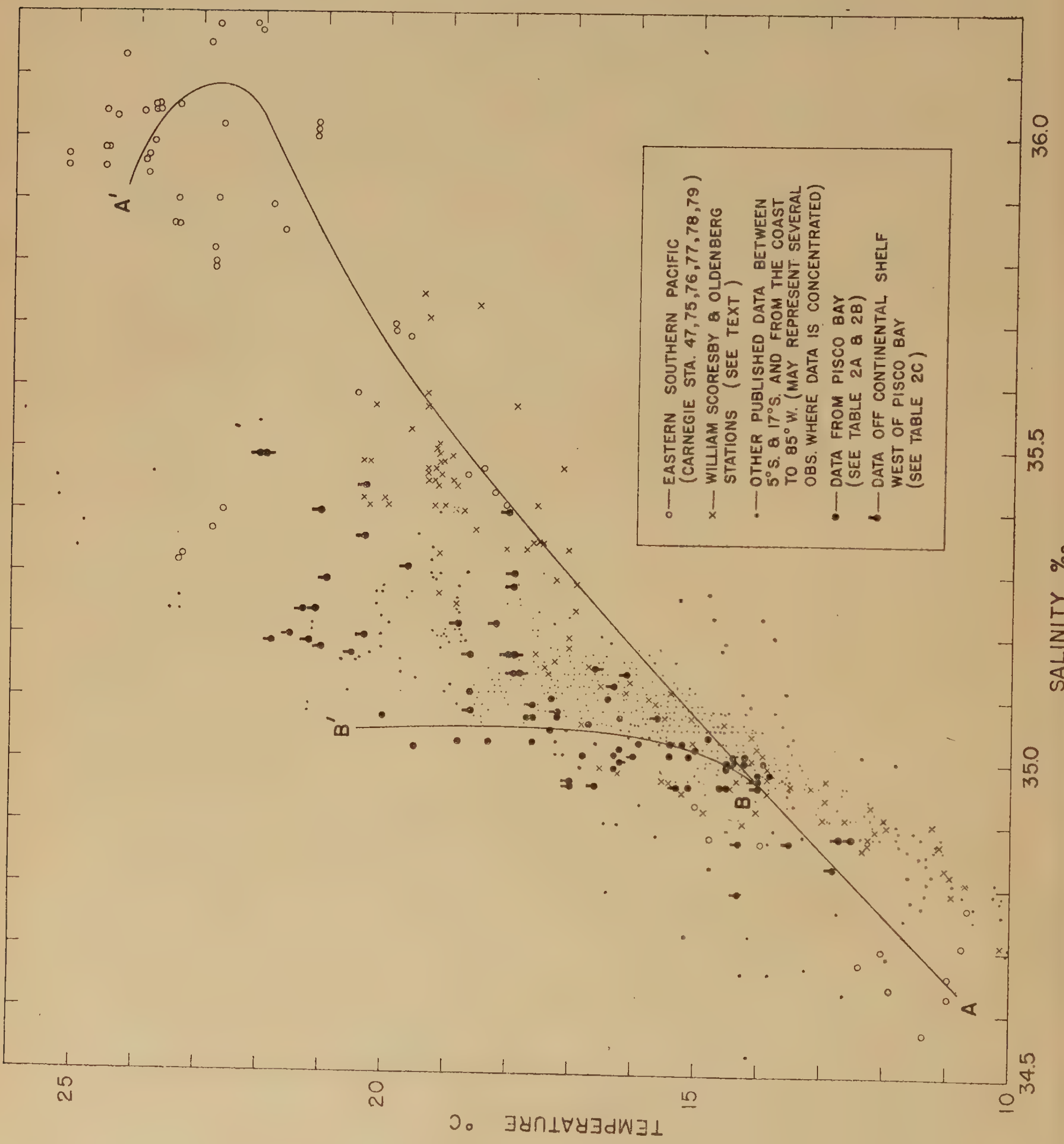


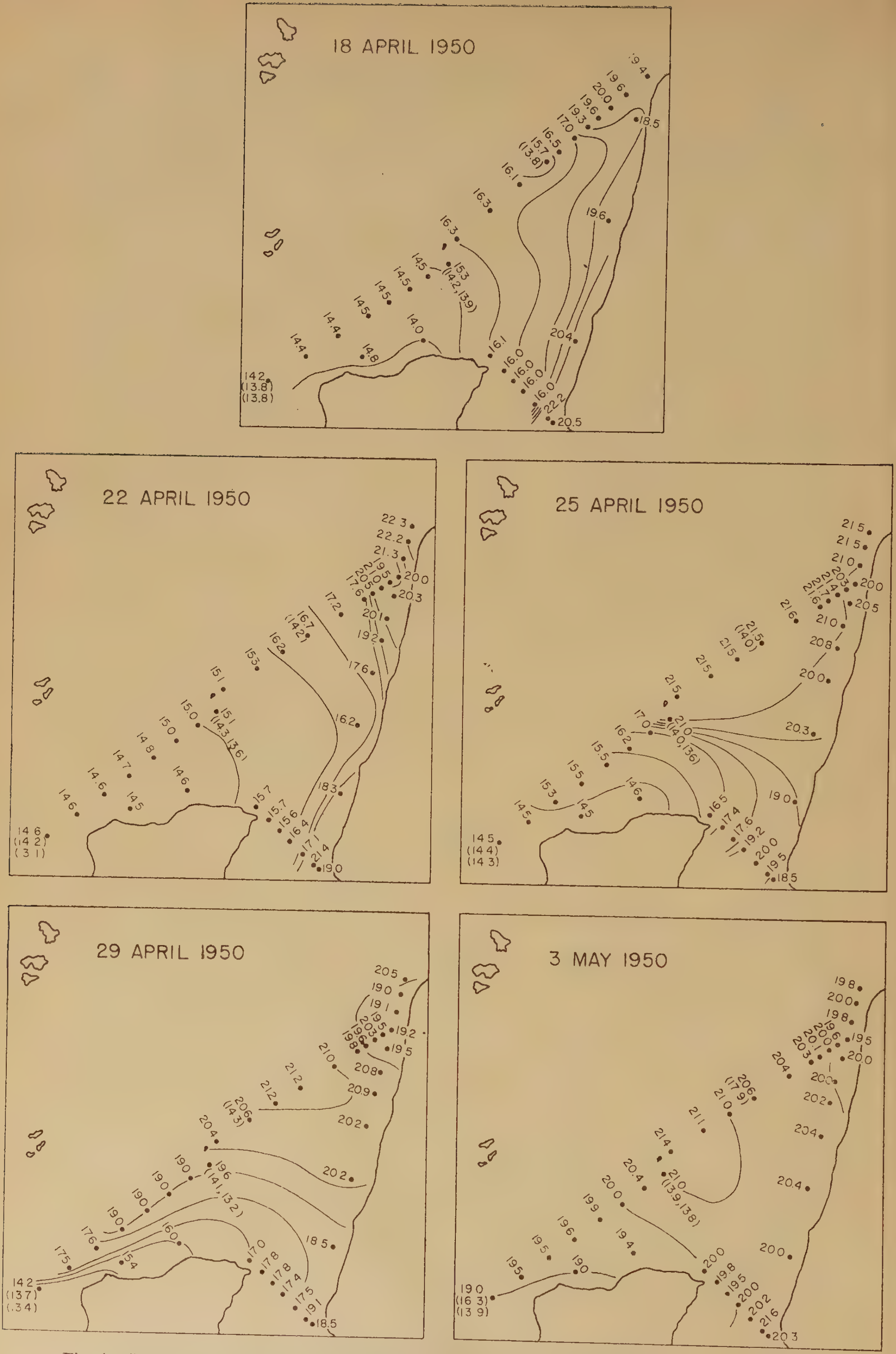
Fig. 3. T-S diagram comparing characteristics of inshore water with that of the Eastern South Pacific as a whole.

as already reported by GUNTHER (1936) and SVERDRUP (1930). Our stations to the west of Chincha Norte indicate that even within 100 miles of the island these temperatures may be found at depths of 100 to 200 metres. In short, the uniformity of the salinities in Pisco Bay may be accounted for by upwelling from some subsurface layer and the higher temperatures in all probability by solar warming *in situ*, as will be shown below.

It is possible to estimate roughly whether solar warming in the absence of marked upwelling could produce the higher temperatures recorded in 1941. In these computations, it is necessary to simplify the conditions which probably existed in the bay by neglecting currents and horizontal mixing. On the other hand, a certain amount of downward mixing must be assumed to account for observed temperatures at a station close to Chincha Norte where weekly temperatures at 10-metre intervals down to 50 metres were recorded for the latter part of 1940 and much of 1941 (Table 3). Averages for this water column reveal a noticeable warming as early as 29 December 1940 (Table 3), a warming which continued until mid-March 1941. Thereafter, it cooled gradually until mid-June, when the observations were suspended. The greatest increase between any two sets of observations in the average temperature for the 50-metre column was 2·1°C (Table 3) between 19 January and 16 February 1941. To raise the temperature of this column of water by 2°C requires 10,000 gram calories per square centimetre of sea surface or 358 gram calories per square centimetre per day. For the season and latitude under consideration, it is estimated that the average radiation from sun and sky amounts to at least 432 to 648 gram calories per square centimetre per day (SVERDRUP, JOHNSON and FLEMING, 1942, Table 25). If it is assumed that reflection from the water surface is negligible (SVERDRUP, JOHNSON and FLEMING, 1942, Table 26) and that all the radiation enters the water it would take between fifteen and twenty-three days to produce the observed warming. Consequently, only 55% to 82% of the heat available appears to have been required to produce the observed temperature increase.

The most extreme temperatures recorded within the Bay can also be accounted for in this way. The higher temperatures appear to emanante from the inner part of the Bay off Pisco (Fig. 4; SCHWEIGGER, 1942) in an area (Fig. 1) which roughly coincides with depths of less than 20 metres. The same number of calories entering through the surface will increase the average temperature of shallow waters more than that of deep. Thus, during the period required to warm the 50-metre column close to Chincha Norte by 2°C, the temperature off Pisco would have risen by perhaps 5°C and in Paracas Bay by 10°C. This means if we assume that the water throughout the Bay averaged roughly 17·4°C at the start and warmed to 19·4°C at Chincha Norte the temperature off Pisco might have risen to 22·4°C and in Paracas Bay to 27·4°C during the same period. Except for the latter, similar surface temperatures have frequently been reported (SCHWEIGGER, 1942, VOGT, 1942; AVILA, 1949, 1950. See also Table 2).

Thus far, it has been assumed that a certain amount of heat was mixed downward through wave action or some such turbulent process, but during periods of calm, a large percentage of the warming would take place in the upper metre of the water mass (SVERDRUP, JOHNSON and FLEMING, 1942, Table 28). Under these conditions in midsummer (January-February), one could expect for each day of calm to find an increase of 2·38°C to 5·35°C at the surface. Increases of 1·8°C to 2·4°C (SCHWEIG-


18 APRIL 1950
19.4
19.6
20.0
19.6
19.3
17.0
18.5
16.5
15.7
(13.8)
16.1
16.3
19.6
16.3
14.5
15.3 (14.2,13.9)
14.5
14.5
14.5
14.0
14.4
14.4
14.8
16.1
20.4
16.0
16.0
16.0
16.0
22.2
20.5
14.2 (13.8) (13.8)
22 APRIL 1950
22.3
22.2
21.3
19.5
21.0
20.5
17.6
20.0
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17.2
20.1
16.7 (14.2)
19.2
16.2
15.5
17.6
15.1
15.1 (14.3,13.6)
15.0
15.0
16.2
14.8
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14.5
14.6
18.3
15.7
15.7
15.6
16.4
17.1
21.4
19.0
14.6 (14.2) (3.1)
25 APRIL 1950
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21.6
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21.5 (14.0)
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20.6 (14.3)
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20.2
19.0
19.6 (14.1,13.2)
19.0
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18.5
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14.2 (13.7) (.34)
3 MAY 1950
19.8
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20.0
20.4
20.6 (17.9)
20.0
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20.2
21.1
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20.4
21.0 (13.9,13.8)
20.0
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20.2
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20.3
19.0 (16.3) (13.9)

Fig. 4. Surface temperatures collected by Señor Enrique Avila. Temperatures in parentheses at 10 and 20 metres respectively.

GER, 1942, Map 22; AVILA, 1950) have actually been reported between 6 a.m. and about 2 p.m. and of 4·5°C in a twenty-four hour period at Chincha Norte (VOGT, unpublished data, January 1940).

In addition to these isolated examples, the surveys made of the inner portion of the Bay in April 1950 (AVILA, 1950) illustrate the same sort of warming over a considerable area (Fig. 4). It may be assumed that the water in the Bay had upwelled very shortly before his surveys started, because the temperatures were 14·2°C at 10 metres and 13·9°C at 20 metres. Only the shallowest layers in the inner part of the Bay showed any significant warming (Fig. 4). With an estimated 410 to 432 gram calories per square centimetre per day in this latitude in April (SVERDRUP, JOHNSON and FLEMING, 1942, Table 25) there was enough heat to warm a layer about 10 metres deep by 1°C in about two and a half days. An increase of 1°C was actually observed off Pisco between 18 and 22 April 1950 (Fig. 4). Similarly, it might be expected that the observed increase of 4·8°C between 22 and 25 April was restricted to a shallower depth indicating that there had been little mixing. The slight decrease at the surface between 29 April and 3 May does not necessarily indicate an intrusion of cold water, but rather a mixing down to at least 10 metres (Fig. 4), since the average temperature had increased to that depth by 1·5°C (cf., FREEMAN, 1953). At the northerly entrance to the Boquerón, however, the increase in temperature is nearly twice as great (i.e., 3·5°C) as could be accounted for by solar radiation alone. In situations such as this, one can only assume in the absence of any precise information that local water movements may in some way account for the increase. In any event, the area with water as warm as 15°C to 21°C or more was progressively expanding and moving toward the Boquerón between 18 April and 3 May (Fig. 4).

It also appears more reasonable to explain the existence of warm water in the inner part of the Bay as resulting from water warming over shallow bottom rather than from the river outflows. Recent studies[14] of rivers with a discharge several hundred times greater than those entering Pisco Bay have provided a convenient method for computing the effect of river effluent on adjacent bodies of water. It is obvious from these that the relatively small streams entering Pisco Bay could only have an infinitesimal effect on the salinity of the area.[15] The same conclusion could

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[14] FORD, 1949; KETCHUM, 1950, 1951, 1951a; KETCHUM, REDFIELD and AYERS, 1950.

[15] The fraction of fresh water (F) in any sample required to reduce the salinity observed at the time of my survey (i.e., about 35‰ by merely one part per thousand over the surface of the Pisco Bay area is found by the following relationships (KETCHUM, REDFIELD and AYERS, 1950, p. 28):

$$F = \frac{35 - 34}{35} = \frac{1}{35} = 0{\cdot}0286.$$

The general area under consideration is roughly 400 square miles or about 14·8 × 10^9 square feet. For convenience in computation, we may take into consideration only the surface layer to a depth of one foot. The volume of fresh water required to decrease the salinity by only one part per thousand is found by multiplying the fraction (F) by the volume of water in the surface layer to a depth of one foot :

$$0{\cdot}0286 \times 14{\cdot}8 \times 10^9 \text{ cubic feet}$$
$$= 423 \times 10^6 \text{ cubic feet.}$$

The flow from both rivers entering the area is reported to be roughly 76,000 litres per day (SCHWEIGGER, 1942, p. 80). Therefore before enough fresh water could enter from this source to effect a change of one part per thousand in the salinity, it would take: $\frac{423 \times 10^6}{2{\cdot}63 \times 10^3} = 160{,}000$ days or more than 400 years, provided that all other processes which might tend to increase or decrease the salinity be inactive.

be reached by considering the heat contribution of the rivers. We can, therefore, dismiss the discharge from the two rivers as a means of increasing the surface temperature of Pisco Bay in any significant way, especially since the salinity normally tends to increase, not decrease, with temperature (Fig. 3).

Solar warming then can account for most of the sudden increases in temperature which have been observed in Pisco Bay from place to place and almost from hour to hour.

COOLING IN PISCO BAY

The cool water on the Peruvian coast upwells from subsurface layers with a temperature between 13°C and 14°C. (GUNTHER, 1936; SVERDRUP, 1930). Indications are that this water rises to the surface in the general vicinity of Punta Huacas south of the Boquerón (Fig. 1). The coldest water is frequently found there and extending northward into the Bay toward the Ballestas and Isla Blanca (Fig. 4). Not infrequently, surface temperatures below 15°C are found in this general vicinity (AVILA, 1949; 1950; MURPHY, 1923; SCHWEIGGER, 1942) and water of 13°C has actually been observed at the surface close to Isla Blanca. In 1941, the coldest water was somewhat warmer (between 14°C and 15°C), but nevertheless it too was found south of San Gallán at depths of 10 metres or more. Elsewhere it occurred as deep as 50 metres. In other years, as exemplified by 1950 (Fig. 4), temperatures of 14·0°C and 14·5°C occur over much of the southwestern portion of the Bay and its approaches and within 10 metres of the surface elsewhere.

As mentioned earlier, temperatures recorded in Paracas Bay are not as high as might be expected in an isolated shallow bay. The temperatures there the latter part of April 1940 (Fig. 4) indicate that the water east of Punta Pejerry was no warmer than much of Pisco Bay. On the other hand, close to La Puntilla, the morning temperatures was consistently cooler than one taken at the end of the circuit in early afternoon. It looks then as if cool water from the Boquerón flows north of the Paracas Peninsula and around Punta Pejerry into Paracas Bay. It may be that this is part of a counter clockwise circulation in the Bay, which would tend to develop as a result of the prevailing southeasterly wind.

This sort of temperature distribution means that with each pulse of upwelling, cold water surges into the Bay through the Boquerón. It is not possible to determine with existing data whether each such pulse flushes out the bay or whether the amount of water entering the Bay varies depending upon the strength of the upwelling. The cold temperatures so close to the surface in April 1950, together with the fact that most of the somewhat warmer surface temperatures observed in the Bay at that time can be accounted for by warming *in situ* of relatively short duration certainly seems to suggest that flushing may at times be practically complete.

In the computations of warming from solar radiation, mixing was considered as a mechanism for distributing heat downward from the surface. However, the Bay is not an isolated body of water as this might imply. Under somewhat different circumstances, mixing can also be a means of cooling (cf., FREEMAN, 1953). The warm temperatures observed at the surface with a sufficiently strong wind would mix with the cold water existing below 10 metres with the result that the surface temperature would be considerably reduced. Under such circumstances, surface cooling is not indicative of a new intrusion of cold water. Once again, it appears that surface temperatures are not reliable when interpreting hydrographic conditions.

TEMPERATURES IN "CRASH" AND "NORMAL" YEARS

Surface temperatures of 20°C to 21°C or even higher occur over large portions of the Bay much of the year, in both "crash" years and "normal" ones. They are therefore not a reliable index for differentiating between them. On the other hand, subsurface temperatures may prove useful in this respect. In a "crash" year, such as 1941, the warming process is predominant, apparently through a cessation of upwelling for a more or less prolonged period. In the absence of upwelling, the water in the Bay is warmed by the sun. Through mixing the warming extends downward depressing the isotherm for 14°C to a depth of 50 metres or more and it may then remain deep for as long as six months from midsummer to midwinter (Table 3). Even in the absence of upwelling, some seasonal cooling takes place in late spring before the heavy cloud develops, a cloud which hangs over the coastal region perhaps eighty per cent of the time during the winter months (U.S. Navy Hydrographic Office, 1938). Despite this cooling, the isotherm for 14°C tends to remain deep, until upwelling again becomes active.

In a "normal" year, such as 1950, the cooling process appears to dominate except at the very surface, presumably because of repeated upwelling, possibly as often as every two or three weeks. Were upwelling more infrequent, it might be expected that the water column down to at least 50 metres would warm by about 2°C, as it did in 1941. Judging from the situation in April 1950 (Fig. 4), this does not happen, but rather the 14°C-isotherm lies within 10 to 20 metres of the surface and the temperature for the water column down to 50 metres averages close to 14·5°C rather than 18°C as in 1941. Superficial temperatures may, however, be as high as in a "crash" year following several days of calm or light winds.

ANNUAL TEMPERATURE CYCLE

One further point needs to be considered in trying to understand the hydrographic situation in Pisco Bay, namely, the annual temperature cycle. In most earlier discussions, this has not been stressed, perhaps because the significant temperature changes have always been so sudden and catastrophic. Nevertheless, such a cycle appears to exist in the surface layers, at least, for certain sectors of the coast (SCHWEIGGER, 1951; U.S. Coast and Geodetic Survey, 1948; U.S. Navy Hydrographic Office, 1938) with an average difference between summer and winter of roughly 7°C. Temperature differences of this magnitude in such low latitudes could readily be explained by the low dense cloud present nearly 80 per cent of the time during the months of July, August and September in contrast to practically clear skies from January through April (U.S. Navy Hydrographic Office, 1938). Such a cycle is revealed when surface data are averaged over a considerable number of years (SCHWEIGGER, 1951). From these, it appears that the extreme surface temperatures for any year along the Peruvian coast at least as far south as 12°S, whether in "normal" or "crash" years is usually as great as any ever recorded in Pisco Bay (SCHWEIGGER, 1951).

Some caution must be used, however, in interpreting averaged data of this sort, as the actual situation may be obscured. This has been demonstrated in studies of the Gulf Stream, for example (FUGLISTER, 1951). In a warm year, such as 1941, a year which was characterized by an almost complete absence of upwelling, the annual cycle was apparent in both surface and subsurface layers. In more usual years, such as 1950, it seems likely that the temperature cycle for the water column as a whole will be completely obscured by upwelling, which may also keep the surface temperatures low. It might also be expected that the surface temperatures might fluctuate markedly increasing during periods of calm or light winds, but decreasing with stronger winds.

COMPARISON WITH OTHER AREAS

Temperatures of the Peruvian littoral are not as extreme as those in some temperate regions, such as along the east coast of the United States. There, for example, at the warmest season, the surface temperatures from Chesapeake Bay to Cape Cod (BIGELOW, 1933, Fig. 35) are the same or even a little higher (i.e., 23°C to 26°C) than in Pisco Bay. The winter temperatures, however, are very much lower, ranging from about 2°C to 8°C.

Likewise, in midsummer, when a marked thermocline is established, there may be a considerably greater contrast in the vertical temperature distribution off the east coast of the United States. There a pool of cool water of from 6°C to 8°C lies at depths of 40 metres or more (BIGELOW, 1933, Figs. 41-44), but the surface temperature may be as high as 25°C. Within 25 metres there may thus be a vertical temperature gradient of 16°C, a range greater than any ever recorded on the Peruvian coast.

Similarly, the salinities regularly occurring along the Peruvian coast are much more uniform than along the east coast of the United States. Ordinarily, on the coast of Peru, salinities do not vary by as much as 1‰, never by more than 2‰. To be sure, at the mouth of a stream, this might not be true, but freshening from this source, as already pointed out, is insignificant for the Coastal Current as a whole. In contrast, off the east coast of the United States, crossing the continental shelf somewhat north of Cape Hatteras, the salinities may vary between 29·96‰ to 35·9‰, a gradient of 6‰. Vertically, in as little as 20 metres, the gradient may be 2·95‰ (29·96‰ at the surface and 32·91‰ at 20 metres) (BIGELOW and SEARS, 1935, Fig. 8) and at one locality there may be an increase from 29·65‰ to 32·24‰ in a fortnight (BIGELOW and SEARS, 1935, Fig. 25). These are extreme values, but nevertheless they may be expected with some regularity over considerable areas at certain times of year.

In other areas, such as the Bay of Fundy, the annual temperature range (8·6°C to 10°C) and the annual salinity range (0·7‰ to 1·4‰) (BAILEY, MACGREGOR and HACHEY, 1954) are roughly the same as off the Peruvian coast. In the Mediterranean, the annual temperature limits (i.e., about 13°C to about 26°C) (RODRÍGUEZ-RODA, 1953) are almost identical with the most extreme temperatures of the Peruvian Coastal Current. Thus, the temperatures and salinities of the Peruvian Coastal Current are not unique nor are they extreme, a situation that appears to have been overlooked.

BIOLOGICAL CONSIDERATIONS

There are two types of biological disasters, both associated with high water temperatures and formerly considered as a consequence of " El Niño." The first is the disappearance of the anchovies. This is the cause of death from starvation among the guano birds. Warming *per se* could be responsible for this type of disaster despite the relatively narrow temperature limits of the Peruvian Coastal Current. A considerable number of the diatom species occurring there are also found in more temperate regions. It may be that the lower temperatures of the Current are near the upper limits of their tolerance. On the other hand, it might be that the supply of nutrient salts becomes depleted in the absence of upwelling. Thus the production of diatoms would be restricted. In either event, the anchovies would go elsewhere in search of food. These points need clarification.

The second type of disaster is associated with the appearance of "red water" ("aguaje"). There are numerous examples elsewhere that this is usually accompanied by a mass mortality of fish and larger invertebrates.[16] "Aguaje" ("red water") has most frequently been reported as resulting from an incursion of "El Niño" (LAVALLE y GARCIA, 1918; SHEPPARD, 1931). It has also occurred in water of offshore origin (GUNTHER 1936a, pp. 57-58) and in October 1941 it was found in upwelled water between Chincha Norte and Tambo de Mora.

To illustrate the complexity of the problem, the situation existing at the time of the "aguaje" of October 1941 is recorded here in some detail. Several million odd cormorants nesting in the Ballestas were going out each day in search of food and sufficient numbers of anchovies were available to prevent a mass starvation of the birds and at times even to attract whales. One Sunday, thirteen were spouting at one time within view of Chincha Norte and schools of anchovies were breaking the surface. During this period of plenty, there are notations in my records which suggest that all was not going well in the area. Thus, on 27 October, going north toward Tambo de Mora, a station was taken where the temperature at the time was not extraordinarily high (20·5°C at the surface, 16°C at 5 metres and 14·7°C at 43 metres). The zooplankton nets came up loaded with a yellow-brown slime from decaying phytoplankton. We have no information as to the organisms concerned, but it is possible that they may have been the naked flagellate (VOGT, 1942, Photo A, opposite p. 111) observed at Pisco in considerable numbers at about this time. Two days later (29 October), there were dead sea slugs on the beach at Chincha Norte and on 30 October, dead "lissas" were reported at La Puntilla. Meanwhile a visitor from Lima (1 November) reported a putrefactive stench, characteristic of an "aguaje" all the way down the coast from Callao (cf., BRONGERSMA-SANDERS, 1948; RAHM, 1927; WOODCOCK, 1948). Yet that same day the birds had fed in the Bay and over the weekend (3-4 November), Pisco Bay was teeming with life, the whales mentioned above, anchovies, Munida, gray gulls, etc., in addition to the usual guano birds.

In most cases, "red water" is chiefly due to a very dense concentration of dinoflagellates (BRONGERSMA-SANDERS, 1948), with the individuals in any one swarm usually belonging to but one species. From one half to one million cells per litre merely give the appearance of a dingy chocolate colour to the water, a colour often seen on the Peruvian coast. If the number doubles the water becomes distinctly red (ALLEN, 1942). Apparently, dinoflagellates bloom most frequently at times when the water temperature is relatively high. They occur in boreal waters after the flowering of diatoms (BIGELOW, 1927), when the water there is warmest. Just as is the case for diatoms (BIGELOW, LILLICK and SEARS, 1940, p. 169), no one factor appears to stimulate their increase. Recently, it has been suggested that small water masses of low salinity appear to be favourable for the growth of a " red tide " (SLOBODKIN, 1953). Certain species of dinoflagellates do actually show a maximal reproductive rate when salinities are low (BRAARUD, 1951; NORDLI, 1953). In view of the extremely slight runoff from streams entering Pisco Bay, it seems unlikely that similar conditions favour the development of an " aguaje " on the Peruvian coast. Earlier, KETCHUM and KEEN (1948) found 2½ to 10 times the maximal total of phosphorus to be expected in the sea during a " red tide " off the west coast of Florida. Thus, they seem to exclude the possibility that the blooms necesarily depend on upwelled, nutrient rich water. In some cases, it is believed that dinoflagellates become concentrated by convection cells (BARY, 1953). In short, it is unlikely that optimal conditions are the same for all species which may cause " red water."

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[16] BHIMACHAR and GEORGE, 1950; BRONGERSMA-SANDERS, 1948; CHEW, 1953; CONNELL and CROSS, 1950; COPENHAGEN, 1953; DAVIS, 1948; GUNTER, *et al.*, 1948; HAYES and AUSTIN, 1951; SOMMER and CLARKE, 1948.

An intrusion of a foreign water mass such as " El Niño " or offshore water is not a prerequisite for either type of biological disaster. It is now established that the upwelled water of the Peruvian Current may also produce such a bloom when it has warmed in the surface layers to a temperature of 20°C as described earlier. It seems likely that little further headway can be made in determining limiting factors other than heat, until some record of the species concerned together with the environmental conditions is made.

DISCUSSION

The problem presented above is obviously not a simple one and is far from solved. Much headway could be made with more quantitative information of the upwelling process similar to that obtained recently along the Californian coast (California, Marine Research Committee, 1953). There, not only have many more centres of upwelling been discovered in the last five years than had been previously known, but also a method is in course of development for measuring the intensity of upwelling in different localities. These studies show that the intensity of upwelling fluctuates from year to year, just as appears to be true on the Peruvian coast. An attempt was made in the work along the California coast to correlate the intensity of upwelling with an increasing wind stress. Although weather cycles are recognized on the Peruvian coast (RUDOLPH, 1953; WILLETT and RUBIN, 1953) sufficient data have not accumulated there to determine any relationship between upwelling and meteorological phenomena. Such data, together with model studies in the laboratory (VON ARX, 1952) should provide significant clues for an understanding of the ecology of the Peruvian Coastal Current.

Consideration must also be given in future to the cycle of nutrient salts. Throughout the present paper, it has been assumed that they are usually in excess and that their disappearance when upwelling ceases may indirectly account for the disappearance of the anchovies. The question is complicated by the fact that it is not known whether the excreta of the birds make any significant contribution to the abundance of nutrients in the water. In a very limited area within a bay on Long Island, New York, it is estimated that four million ducks produce 2·7 million pounds of nitrogen and 0·82 million pounds of phosphorus per year (Woods Hole Oceanographic Institution, 1952). The uric acid deposited in the water is quickly changed into soluble nitrogenous compounds by bacteria. At the height of the season, small green algae are extremely numerous rather than more characteristic diatoms and dinoflagellates, possibly due to the abnormal nitrogen-phosphorus ratio. This suggests that in the vicinity of a guano island, despite a substantial deposit of guano on the island itself, there may also be a significant contribution to the surface waters. This might account for the dense population of a large naked flagellate in the latter part of October, when several million cormorants were nesting in the Ballestas.

Clarification of these two questions together with work presently in progress on the life history of the anchovy will go a long way toward accounting for the fluctuations in the amount of guano deposited on the islands from year to year and to an understanding of the high productivity of an area of active upwelling.

SUMMARY

1. The ecological situation in the Peruvian Coastal Current is reviewed.

2. It is suggested that during catastrophic periods, warming *in situ* in the absence of active upwellings is perhaps more frequent than a phenomenal incursion of " El Niño " like that of 1925 or of warm offshore water. Contributions from rivers appear negligible for the area as a whole.

3. Some consideration is given to the cooling process and its possible effect on the annual temperature cycle.

4. The annual temperature range appears to be about 7°C. and the salinity range less than 2‰, compared with a temperature range of 20°C or more and a salinity range of perhaps 6‰ in temperate coastal waters.

5. There are two types of biological disasters, both usually associated with warm water and formerly attributed to " El Niño." One is the series of events initiated by disappearance of the anchovies, the other by the development of " red water." The latter has been found not only as a consequence of an incursion of " El Niño " and of warm offshore water, but also in upwelled water which has warmed in the surface layers.

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Woods Hole Oceanographic Institution, Woods Hole Mass., U.S.A.

Table 1. *Data for stations occupied in vicinity of Cabo Blanco and Lobitos from "El Lobito"*

Station	*CB* 1-2 *mi. W. Lobitos buoys*		*CB* 2-6 *mi. W. Lobitos buoys*		*CB* 3-14 *mi. W. Lobitos buoys*		*CB* 4-1 *mi. W. C. Blanco*	
Date	17 *Jan.* 1942		17 *Jan.* 1942		17 *Jan.* 1942		19 *Jan.* 1942	
Total depth (*m*)	40		*more than* 200		—		85	
Depth in (*m*)	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰
0	21·4	34·80	21·4	34·65	21·8	34·78	20.6	34·76
5	21·2	broken	21·3	34·65	21·6	34·78	20·5	34·78
10	21·1	34·81	21·2	34·70	21·2	34·79	20·5	34·76
25	20·0	34·81	21·0	34·70	21·0	34·81	18·9	34·85
39	18·7	broken	–	–	–	–	–	–
50	–	–	18·6	34·94	18·4	34·97	17·6	34·99
75	–	–	–	–	–	–	17·0	–
100	–	–	16·5	35·03	16·3	35·07	–	–
200	–	–	14·5	34·99	14·6	broken	–	–

Station	*CB* 5-9 *mi. W. C. Blanco*		*CB* 6-20 *mi. W. C. Blanco*		*CB* 7-32-35 *mi. W. C. Blanco*		*CB* 8-1·5 *mi. W. C. Blanco*		*CB* 9-9 *mi. NW. C. Blanco*	
Date	19 *Jan.* 1942		19 *Jan.* 1942		20 *Jan.* 1942		21 *Jan.* 1942		21 *Jan.* 1942	
Total depth (*m*)	—		—		—		100		—	
Depth in (*m*)	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰
0	21·6	34·72	22·0	34·70	22·6	34·74	21·1	34·74	21·6	34·70
5	21·5	34·70	21·9	34·70	22·5	34·72	21·0	34·74	21·6	34·72
10	21·1	34·76	21·8	34·69	22·2	34·72	19·6	34·82	20·5	34·83
25	20·1	34·85	20·0	34·85	22·1	34·74	18·6	34·87	19·6	34·87
50	18·6	34·90	18·8	34·97	18·4	35·01	16·1	35·01	18·6	34·94
95	–	–	–	–	–	–	15·9	35·01	–	–
100	16·8	35·01	16·8	35·03	16·5	35·07	–	–	16·5	35·02
200	14·3	34·97	14·7	34·99	15·0	35·03	–	–	13·8	34·97

Table 2. *Data for stations occupied in the vicinity of Pisco Bay in* 1941.

A. Regular series of stations

Sta. P 1. Roughly 5 miles east of Chincha Norte.

Date	5 *Sept.*		16 *Sept.*	22 *Sept.*	3 *Oct.*	23 *Oct.*	6 *Nov.*	24 *Nov.*	8 *Dec.*
Total depth (*m*)	67		69	57	57	58	58	59	47
Depths in (*m*)	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Temp. in* °*C.*	*Temp. in* °*C.*	*Temp. in* °*C.*	*Temp. in* °*C.*	*Temp. in* °*C.*	*Temp. in* °*C.*
0	–	–	17·8	17·0	16·1	16·8	16·9	19·0	16·0
5	16·7	35·06	17·3	17·0	16·0	16·8	16·9	15·8	15·6
10	–	–	16·1	17·0	15·6	16·7	16·4	15·5	15·5
25	14·8	–	15·1	15·1	14·8	15·0	15·3	15·0	14·8
50	14·3	–	14·4	14·7	14·4	14·7	15·0	15·0	14·6
60	–	–	14·4	–	–	–	–	–	–

Table 2 (continued)

Sta. P 2. Roughly 5 miles toward Pisco from Station P 1.

Date	*5 Sept.*		*22 Sept.*	*3 Oct.*	*23 Oct.*	*6 Nov.*	*24 Nov.*	*8 Dec.*
Total depth (m)	13		10	9	8	7	9	9
Depths in (m)	*Temp. in °C.*	*Sal. in ‰*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*
0	–	–	18·3	15·6	16·5	18·0	16·6	16·0
4	19·4	–	–	–	–	–	–	–
5	–	35·06	18·1	15·6	16·1	16·5	16·2	15·6
8	18·0	–	17·8	–	–	–	–	–

Sta. P 3. Roughly 5 miles toward Ballestas from Station P 2.

Date	*5 Sept.*		*16 Sept.*	*22 Sept.*	*3 Oct.*	*23 Oct.*	*6 Nov.*	*24 Nov.*	*8 Dec.*
Total depth (m)	55		68	59	56	54	59	63	61
Depths in (m)	*Temp. in °C.*	*Sal. in ‰*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*
0	–	–	18·3	18·3	16·5	16·7	17·5	17·1	16·6
5	18·6	35·11	17·9	17·2	15·6	16·4	16·8	16·3	15·4
10	–	–	16·6	16·3	15·4	15·8	16·4	15·1	15·1
20	15·2	–	–	–	–	–	–	–	–
25	–	–	15·2	15·0	14·7	14·8	15·8	14·9	14·7
40	14·5	35·00	–	–	–	–	–	–	–
50	–	–	14·5	14·6	14·4	14·6	15·0	14·6	14·6

Sta. P 4. Roughly 5 miles west of Ballestas.

Date	*9 Sept.*		*22 Sept.*	*3 Oct.*	*23 Oct.*	*6 Nov.*	*24 Nov.*
Total depth (m)	122		119	110	121	120	118
Depths in (m)	*Temp. in °C.*	*Sal. in ‰*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*
0	–	–	17·5	17·1	17·4	19·2	18·0
5	16·8	35·01	17·1	16·0	16·2	16·9	17·2
10	–	–	16·6	15·5	16·0	16·4	15·0
25	14·4	35·00	14·8	14·9	15·9	15·7	14·6
50	14·8	35·04	14·2	14·2	14·9	14·8	14·5
75	14·6	34·96	14·1	–	–	–	–
100	–	–	14·0	14·0	13·9	14·2	14·2

Table 2 (continued)

Sta. P 5. Roughly 5 miles west of Chincha Norte.

Date	*9 Sept.*		*24 Sept.*	*7 Oct.*	*25 Oct.*	*8 Nov.*	*28 Nov.*	*10 Dec.*
Total depth (m)	122		124	134	117	120	127	121
Depths in (m)	*Temp. in °C.*	*Sal. in ‰*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*
0	–	–	17·1	16·3	17·0	18·0	18·0	16·2
5	16·2	35·00	17·0	15·6	17·0	18·0	17·0	16·0
10	–	–	15·5	15·6	17·0	17·8	16·2	15·9
25	14·5	34·99	14·6	14·7	16·1	16·9	15·3	15·0
50	14·0	–	14·2	14·4	14·7	14·6	14·6	14·8
75	13·8	–	–	–	–	–	–	–
100	–	–	14·0	14·2	13·7	13·9	14·5	13·6
115	–	–	13·9	–	13·6	–	–	–
125	–	–	–	14·2	–	–	–	–

Sta. P 6. Roughly 3 miles north of Chincha Norte through 7 October, thereafter 5 miles north of Chincha Norte.

Date	9 *Sept.*		16 *Sept.*	24 *Sept.*	1 *Oct.*	7 *Oct.*	13 *Oct.*	25 *Oct.*	29 *Oct.*	8 *Nov.*	28 *Nov.*	10 *Dec.*
Total depth (m)	87		92	95	91	97	88	95	86	101	97	91
Depths in (m)	*Temp. in °C.*	*Sal. in ‰*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*
0	–	–	17·1	17·7	16·9	17·2	15·8	17·7	20·1	19·8	21·6	17·6
5	19·5	35·02	16·6	17·4	16·0	16·2	15·3	16·0	18·6	18·5	19·4	15·6
10	–	–	16·1	16·5	15·8	16·6	15·1	16·0	15·6	17·2	15·4	15·5
25	15·4	35·01	15·0	15·1	14·7	14·9	14·7	15·1	15·0	15·9	15·1	15·0
50	14·2	–	14·3	14·3	14·3	14·5	14·4	14·5	14·5	14·4	14·7	14·5
70	14·0	34·98	14·1	14·0	14·2	14·2	13·6	14·2	14·5	14·0	–	–
80	–	–	–	–	–	–	–	–	–	–	–	14·0
97	–	–	–	–	–	–	–	–	–	–	14·5	–

Sta. P 7. Roughly 3 miles south of San Gallán and about 3 miles west of Point Huacas.

Date	*11 Sept.*		*9 Oct.*	*14 Nov.*	*2 Dec.*
Total depth (m)	92		93	90	86
Depths in (m)	*Temp. in °C.*	*Sal. in ‰*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*
0	–	–	16·7	15·8	17·6
5	15·0	35·02	15·4	15·8	16·6
10	–	–	15·0	15·4	16·0
25	14·2	35·00	14·9	15·3	15·3
50	13·9	35·00	14·4	14·6	14·6
75	13·8	34·98	14·2	14·4	–
80	–	–	–	–	14·1
100	–	–	–	–	–
150	–	–	–	–	–
180	–	–	–	–	–
185	–	–	–	–	–

Sta. P 8. Roughly 5 miles west of P 7.

Date	*11 Sept.*		*9 Oct.*	*14 Nov.*	*30 Nov.*
Total depth (m)	174		193	190	188
Depths in (m)	*Temp. in °C.*	*Sal. in ‰*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*
0	–	–	17·9	16·6	17·9
5	16·3	34·99	15·9	16·4	17·7
10	–	35·04	15·3	16·0	17·1
25	14·4	–	15·0	15·6	16·6
50	14·8	–	14·2	14·4	14·5
75	–	–	13·9	14·0	–
80	–	–	–	–	–
100	14·4	–	–	–	14·0
150	14·2	–	–	–	–
180	–	–	–	–	13·0
185	–	–	–	13·6	–

Table 2 (*continued*)

	Sta. P 9. Roughly 10 mi. W. of Chincha Norte.	Sta. P 10. Roughly 10-12 mi. N. of P 5.			Sta. PA. Roughly 3 mi. from P 6 toward Pisco.	Sta. PB. Roughly 9 mi. toward Pisco from P 6.
Date	7 *Oct.*	25 *Oct.*	8 *Nov.*	28 *Nov.*	16 *Sept.*	16 *Sept.*
Total depth (*m*)	148	94	114	99	72	25
Depths in (*m*)	*Temp.* in *°C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*
0	16·1	17·1	19·3	19·9	17·6	17·6
5	16·2	16·8	17·7	18·4	17·0	17·2
10	15·7	16·4	17·4	15·5	16·5	17·2
20	–	–	–	–	–	16·0
25	15·0	15·7	16·0	14·9	15·1	–
50	14·7	14·5	14·5	14·7	14·4	–
65	–	–	–	–	14·2	–
75	–	–	–	–	–	–
90	–	14·3	–	14·5	–	–
100	14·2	–	14·0	–	–	–
140	14·0	–	–	–	–	–

B. Miscellaneous stations.

Locality	1 mi. W. Pt. Huacas	About 4 mi. E. of Sta. P6	About 3 mi. toward Chincha Norte from previous column	Chincha Norte Station	Line of stations La Puntilla-Chincha Norte	
					About 4 mi. from La Puntilla	About 8 mi. from La Puntilla
Date	9 *Oct.*	29 *Oct.*	29 *Oct.*	29 *Oct.*	30 *Oct.*	30 *Oct.*
Total depth (*m*)	49	57	79	—	20	39
Depths in (*m*)	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*	*Temp. in °C.*
0	16·2	20·6	20·0	21·1	20·3	19·7
5	16·1	18·5	19·3	18·4	18·0	16·7
10	14·6	15·9	16·9	16·9	16·1	15·3
15	–	–	–	–	15·2	–
25	–	15·0	15·1	15·2	–	15·0
35	–	–	–	–	–	14·9
40	14·8	–	–	–	–	–
50	–	14·6	14·6	14·5	–	–
75	–	–	14·6	–	–	–

Table 2 (*continued*)

Locality	Line of stations La Puntilla-Chincha Norte		About 1 mi. W. Ballesta Is.	About 2 mi. W. Pt. Huacas	About 7 mi. W. Pt. Huacas	Chincha Norte Station	
	12 mi. from La Puntilla	16 mi. from La Puntilla					
Date	30 *Oct.*	30 *Oct.*	31 *Oct.*	31 *Oct.*	31 *Oct.*	6 *Nov.*	28 *Nov.*
Total depth (*m*)	68	65	75	83	202		
Depths in (*m*)	*Temp. in* °*C.*	*Temp. in* °*C.*	*Temp. in* °*C.*	*Temp. in* °*C.*	*Temp. in* °*C.*	*Temp. in* °*C.*	*Temp. in* °*C.*
0	19·6	21·3	16·9	16·9	16·9	20·2	19·9
5	18·4	18·9	16·9	16·7	16·7	19·8	18·5
10	15·6	17·0	15·9	15·9	16·4	17·7	15·8
25	14·7	15·2	14·9	14·8	16·0	15·5	15·1
50	14·4	14·4	14·5	14·6	14·8	14·6	14·6
70	–	–	14·4	–	–	–	–
75	–	–	–	14·4	–	–	–
100	–	–	–	–	14·0	–	–
195	–	–	–	–	13·0	–	–

C. Stations taken from the "Pacific Queen"

Locality	P 11 about 9 mi. toward Tambo de Mora from Chincha Norte		P 12. About 13·5 mi. toward Tambo de Mora from Chincha Norte		P 13. About 4·5 mi. W. P 12	P 14. About 9 mi. W. P 12		P15. 13·5 mi. W. P 12
Date	27 *Oct.*		27 *Oct.*		27 *Oct.*	27 *Oct.*		27 *Oct.*
Total depth (*m*)	38		11		52	91		110
Depths in (*m*)	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*
0	17·6	35·07	20·0	35·07	20·6	18·3	35·03	19·6
5	15·9	35·03	17·3	35·05	16·0	16·3	35·01	19·4
6	–	–	–	–	15·4	–	–	–
7	–	–	–	–	15·2	–	–	–
8	–	–	16·2	35·02	–	–	–	–
10	15·4	35·03	–	–	15·2	16·0	35·01	17·3
25	15·2	35·03	–	–	14·9	15·1	35·01	16·0
43	–	–	–	–	14·7	–	–	–
50	–	–	–	–	–	14·4	35·01	14·5
75	–	–	–	–	–	14·2	35·01	–
100	–	–	–	–	–	–	–	14·2

Table 2 (*continued*)

Locality	P 16. 18 mi. W. P 12		P 17. About 9 mi. W. of Chincha Norte		P 18. About 22·5 mi. W. Chincha Norte		P 19. About 36 mi. W. Chincha Norte	
Date	27 *Oct.*		28 *Oct.*		28 *Oct.*		28 *Oct.*	
Total depth (*m*)	120		129		255		over 200	
Depths in (*m*)	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰
0	18·8	35·03	17·7	35·07	18·0	35·17	18·6	35·17
5	18·3	35·03	17·3	35·10	17·9	35·30	17·9	35·14
10	17·6	35·03	17·2	35·07	17·9	35·17	17·9	35·14
25	16·4	35·10	16·2	35·07	17·9	35·28	17·8	35·14
50	15·1	34·96	14·5	34·96	16·3	35·12	16·1	35·14
100	14·2	35·01	14·0	34·96	14·0	34·97	–	35·16
200	–	–	–	–	12·7	34·88	12·5	34·88

Locality	P 20. About 13·5 mi. W. Chincha Norte	P 21. About 27 mi. W. Chincha Norte		P 22. About 40·5 mi. W. Chincha Norte		P 23. About 112·5 mi. W. Chincha Norte	
Date	15 *Dec.*	15 *Dec.*		15 *Dec.*		16 *Dec.*	
Total depth (*m*)	157	over 200		over 200		over 200	
Depths in (*m*)	*Temp. in* °*C.*	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰
0	17·8	18·6	35·08	21·8	35·19	22·0	35·49
5	17·3	17·6	35·09	21·5	35·20	21·9	35·49
10	16·4	17·2	35·08	21·2	35·19	21·9	35·49
25	16·0	16·6	35·15	18·8	35·22	21·0	35·40
50	15·0	15·6	35·07	17·0	34·96	18·0	35·40
100	15·0	14·0	34·96	14·3	34·87	15·3	34·96
150	13·5	–	–	–	–	–	–
200	–	12·8	34·93	13·0	–	14·3	34·79

Locality	P 24. About 31 mi. E. P 23.		P 25. About 27 mi. E. P 24*	
Date	16 *Dec.*		16 *Dec.*	
Total depth (*m*)	over 200		over 200	
Depths in (*m*)	*Temp. in* °*C.*	*Sal. in* ‰	*Temp. in* °*C.*	*Sal. in* ‰
0	21·3	35·24	21·0	35·18
5	21·1	35·24	20·5	35·17
10	21·1	35·24	20·3	35·20
25	20·9	35·29	20·3	35·36
50	20·3	35·44	19·6	35·31
100	18·2	35·22	17·0	34·97
200	13·5	34·87	16·6	34·96

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* The positions of the stations for 15 and 16 December are inaccurate. A course was set due West until reaching Sta. P 23 and then due East. At about midnight of 16 December, the "Pacific Queen" reached the light at Los Infiernillos about 1° of latitude south of Chincha Norte. This should not be interpreted as necessarily due to a current, since the ship's compass had not been adjusted recently.

Table 3. *Weekly temperature observations down to* 50 m. *in offing of Chincha Norte taken by Mr. William Vogt and Señor Enrique Avila*

	1940									1941			
Metres	13 *Oct.*	20 *Oct.*	27 *Oct.*	10 *Nov.*	17 *Nov.*	1 *Dec.*	8 *Dec.*	15 *Dec.*	29 *Dec.*	5 *Jan.*	12 *Jan.*	19 *Jan.*	16 *Feb.*
0	17·0	17·6	17·9	17·6	17·1	19·0	20·9	19·3	20·6	21·0	21·8	21·7	21·0
10	17·0	17·3	17·3	17·5	16·8	15·0	17·2	17·0	19·1	18·2	19·0	19·2	20·5
20	15·6	15·0	15·2	14·6	16·7	15·0	14·6	15·5	16·2	17·0	17·2	18·3	20·0
30	14·5	14·5	14·5	14·1	16·5	15·0	14·5	15·1	15·9	16·0	16·3	16·0	19·0
40	14·5	14·5	14·5	14·0	15·0	–	14·5	15·0	15·5	15·6	15·5	15·4	18·5
50	14·0	14·0	14·4	14·0	14·5	–	14·0	14·9	15·1	15·2	15·4	15·2	18·2
Average*	15·4	15·0	15·1	15·2	16·1	–	15·6	15·9	16·9	16·9	17·3	17·4	19·5

	1941												
Metres	23 *Feb.*	2 *Mar.*	9 *Mar.*	16 *Mar.*	30 *Mar.*	13 *Apr.*	20 *Apr.*	27 *Apr.*	4 *May*	11 *May*	18 *May*	8 *June*	16 *June*
0	22·0	24·0	24·0	23·3	22·0	19·5	18·7	18·6	19·6	19·9	20·0	19·0	18·4
10	21·0	23·2	23·0	22·2	21·3	19·4	18·6	18·4	19·4	19·2	19·0	18·9	17·0
20	19·6	20·1	20·6	21·8	21·2	19·0	18·0	18·0	18·9	18·3	18·0	18·8	16·2
30	19·5	19·9	19·9	21·2	20·9	18·8	17·4	17·8	18·2	17·8	17·2	18·6	15·7
40	19·2	19·1	19·7	20·9	20·3	18·2	17·2	17·6	17·5	17·2	17·0	18·0	15·0
50	19·0	18·9	19·5	20·3	20·2	18·0	17·0	17·0	17·0	17·0	16·1	17·0	14·9
Average	19·9	20·7	20·9	21·5	20·9	18·8	17·8	17·9	18·4	18·2	17·8	17·4	18·1

	1941											
Metres	7 *Sept.*	14 *Sept.*	21 *Sept.*	28 *Sept.*	12 *Oct.*	26 *Oct.*	2 *Nov.*	9 *Nov.*	23 *Nov.*	30 *Nov.*	7 *Dec.*	14 *Dec.*
0	16·0	17·4	17·4	16·8	15·5	18·5	19·0	17·7	19·6	18·5	16·5	19·0
10	14·5	17·1	17·2	15·9	15·4	18·3	18·0	17·6	16·4	15·6	16·3	17·5
20	14·0	15·0	16·7	14·9	15·2	15·2	16·0	15·8	15·0	15·3	15·7	15·7
30	14·0	14·6	15·3	14·5	15·0	15·1	15·6	15·4	14·7	15·0	15·0	14·7
40	13·9	14·0	14·8	14·4	15·0	14·7	14·8	15·0	14·5	14·7	14·9	14·6
50	13·9	13·9	14·6	14·4	15·0	14·4	14·7	14·7	14·4	14·6	14·8	14·6
Average	14·2	15·6	16·0	15·0	15·2	15·9	16·2	15·9	15·5	15·4	15·5	15·8

* The average for the column 50 metres deep was obtained by adding one-half the surface temperature, one-half the temperature at 50 metres and the temperatures at 10 m, 20 m, 30 m, and 40 m and dividing by 5.

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OBSERVATIONS ON THE MOVEMENTS OF THE PACIFIC GRAY WHALE *ESCHRICHTIUS GLAUCUS* (COPE)

Through the courtesy of the Scripps Institution of Oceanography a party from the Woods Hole Oceanographic Institution was able to conduct a study of the Pacific gray whale, *Eschrichtius glaucus* (Cope), off San Diego, California, during its annual southerly migration. The R/V HORIZON was made available for this work during the period January 28–February 2, 1952. As a part of the over-all study a running plot of the movements of indi-

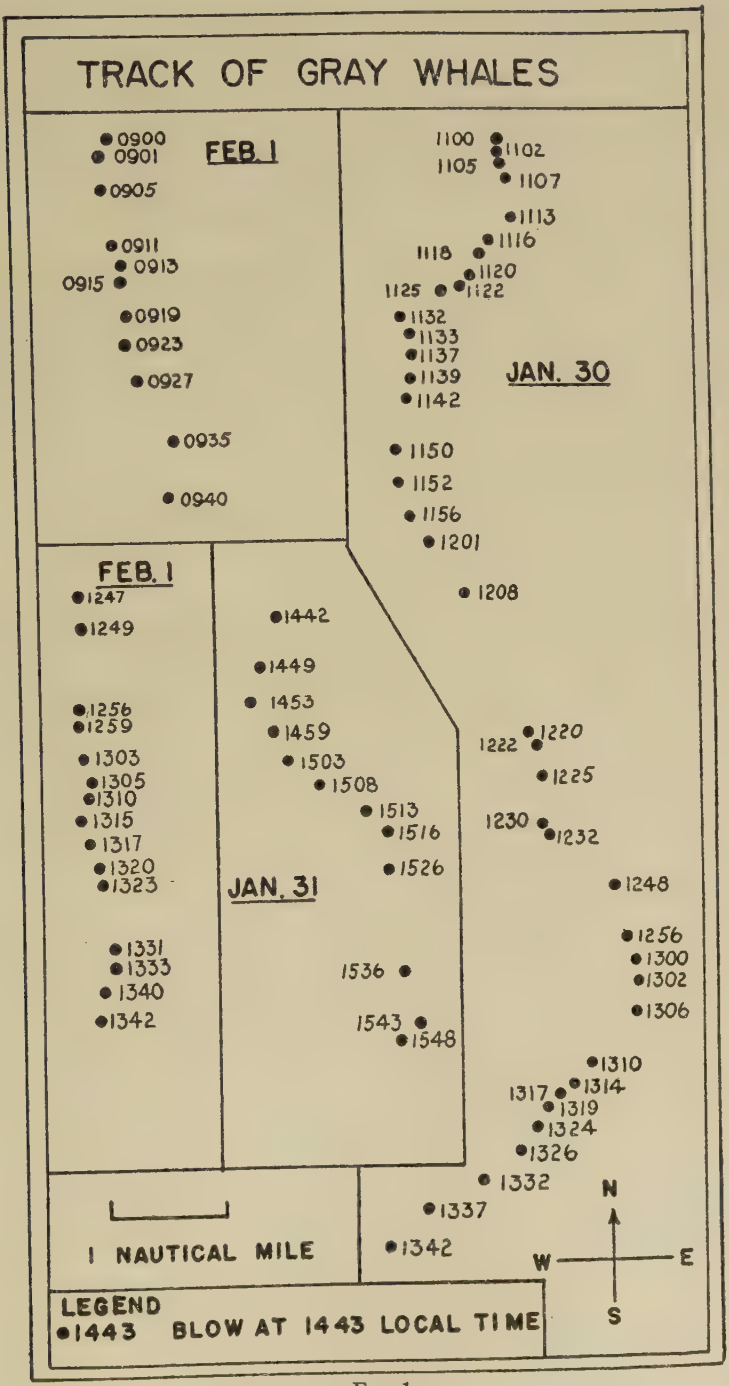
TRACK OF GRAY WHALES
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Fig 1

vidual whales and of the ship was maintained by an observer on the HORIZON. This plot is presented and discussed here.

The area of operations was bounded on the north by the latitude of Point La Jolla, on the south by Point Loma, and on the east by the western edge of the kelp beds, which corresponds roughly to the twenty fathom curve; the width of the whales' "flyway" here appeared to be not much more than a mile. As pointed out by Dr. Carl L. Hubbs, many whales in their southward movement converge on the kelp beds off Point La Jolla. Accordingly it became our practice to lie just off these beds, then pick up passing individuals, and follow them south.

Four runs of between forty minutes' and two hours and forty minutes' duration were made on separate whales—one on January 30, one on January 31, and two on February 1. The plots of these runs appear in Figure 1. To avoid confusion, the ship's track has been omitted. Each dot represents a sighting of a whale at the first blow after a long dive.

This plot suffers from two basic weaknesses. First, it is a dead reckoning plot, based on courses steered by the gyro compass and on speed determined from the shaft revolutions. An average visibility of about 1500 yards in the seasonal fog prevented taking visual bearings on landmarks on the beach for determining geographical location. The second weakness lies in the method of plotting the position of the whale relative to the ship. Visual bearings taken on the first blow after the long dive are accurate to plus or minus one degree. The ranges were estimated by "seaman's eye", and occasionally checked by ultrasonic echo-ranging. These ranges varied from 200 yards to 900 yards. The possible range errors are probably consistent, for one observer did all the plotting.

The speeds averaged over each run were 4.5, 4.6, 4.6, and 4.6 knots. The lowest speed made good in a straight line between blows was 2.4 knots, occurring between 1256 and 1259 local time on February 1. The highest speed between blows was 6.5 knots, measured between 1208 and 1220 on January 30. This period represents the longest dive observed. Although it was foggy, with visibility of 1500 yards, the sea was very calm. While the possibility exists that a blow was missed, the presence of at least two lookouts in addition to the plotter makes this possibility seem remote. Andrews (Mem. Amer. Mus. Nat. Hist(N.S.), 1: 227–287, 1914) states that the gray whale averages about three or four knots when cruising along the shore, and that its maximum speed is seven or eight knots when badly frightened. Walker (Nat. Hist., 58: 248–256, 1949) gives a cruising speed of "six or seven miles per hour" as the average for the migrating whales off La Jolla.

It is felt that this average speed of about 4.6 knots represents a cruising speed of the whale. It was our observation that as long as the HORIZON stayed about ¼ mile away from the whale that we were following, the behavior of that individual was not noticeably differernt from that of others observed at greater distances. However, two of our maneuvers did disturb the whales. First, when the HORIZON came within 200 or 300 yards ahead of the whale, the whale was seen to veer off to the east or west until well clear of the ship, and then resume its normal southerly movement. Second, when ½ lb. blocks of tetryl-TNT were detonated in the water within about 500 yards of the whale, the whale usually maneuvered so radically that it was not sighted again.

The period of the breathing cycle of the whale as observed here was ordinarily between four and five minutes. The cycle usually consisted of three quick blows followed by a long dive. The vapor from the first blow after the long dive was the most dense, hence most easily spotted. The number of blows agrees with Andrews (1914), who reported a period of from seven to eight minutes for the complete cycle when the whale was cruising along shore, and a period of four or five minutes for a female on a straight course.

In conclusion the author would like to express his thanks to the Scripps Institution of Oceanography for the opportunity of conducting this study, in particular to Mr. James M. Snodgrass for his many efforts in arranging details, and to Captain Noel L. Ferris and the officers and crew of the HORIZON for their excellent cooperation.—RALPH F. WYRICK, Contribution No. 672 of the Woods Hole Oceanographic Institution, *Woods Hole, Massachusetts.* (This work was performed under Contract No. NObsr-43270 with the Bureau of Ships, U. S. Navy Department.) *Received November 1, 1953.*

Contribution No. 674

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An Improved Method of Staining the External Organelles of Hypotrichs*

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SUMMARY. A simple, rapid method of staining the external organelles of hypotrichous ciliates is described. Specimens are fixed and stained with Noland's combined phenol-formaldehyde, gentian violet fixative and stain. The staining solution is displaced with iodized glycerine as soon as the external structures are stained to prevent it from coloring the cell body. Cirri and membranelles are stained jet black in sharp contrast to the clear amber background.

MANY HYPOTRICHOUS ciliates are classified to species according to the number and arrangement of the cirri and the shape of the adoral membranelle zone. Students and investigators often find it difficult to identify hypotrichs because these characters are difficult to determine. The structures are so small and transparent in living specimens that high magnification and critical illumination is required to make them visible. In addition most hypotrichs are so active that it requires the utmost patience and skill to keep them within the restricted field of the high dry or oil immersion objective. Few members of this group respond well to narcosis and many species are so delicate that they disintegrate in viscous restraining media. Ordinary histological preparations have generally proved to be unsatisfactory because external structures are obscured against the cytoplasmic mass of the cell body which has a strong affinity for most suitable dyes.

A number of special methods have been devised to differentiate the external structures of ciliates by: 1) impregnating with silver and gold, 2) staining selectively with dyes, and 3) using dyes that stain progressively. The silver-impregnation method introduced by Klein(6,7) provided a means of differentiating various components of the ectoplasm including the basal bodies of cilia and ciliary derivatives. The external structures themselves are not revealed but their location may be determined by the position of these associated structures. Burt(1) has found the method invaluable in revealing the ciliature of the holotrichous genus *Colpoda*. However, the application of Klein's original method to the large or delicate hypotrichous ciliates is limited because one step in the procedure requires that the specimens be dried on the slide. The resulting distortion detracts from the value of the method except when applied to small species or those with rigid pellicles. Von Gelei and Horváth(5) have overcome this difficulty by modifying the Klein technic to eliminate drying. A further refinement by Chatton and Lwoff(2), recently reviewed by Corliss(3), is reported to give excellent results in a number of ciliates.

The silver-impregnation technics are valuable to the taxonomist because they reveal the locations of cilia and their derivatives in permanent preparations. In addition, other ectoplasmic structures of morphological and taxonomic significance associated with the bases of the cilia are differentiated. However, the methods reveal the infraciliature only, so that the relative sizes of the external structures must be inferred from the appearance of their bases. The chief drawback of the silver methods is the time required. It takes hours and in some cases days for their completion. Certain steps require accurate timing which may vary from species to species so that a number of trials must be made before the technic can be established on a routine basis. Frequent changing of solutions, washing, and centrifuging, all result in inevitable losses so that large numbers of specimens must be employed at the start. This limits the application of the silver methods to organisms that can be grown in mass cultures.

A method of staining cilia and their derivatives selectively has been devised by von Gelei(4). Osmic acid-formalin fixed specimens are given prolonged treatments with alum potassium dichromate and ammonium molybdate. The external structures are then stained with toluidine blue and the specimens are dehydrated and cleared. This technic is somewhat superior to the silver-impregnation methods because the external structures and not their bases are differentiated. However, it is nearly as time-consuming, requiring from two to 24 hours. Kirby(6) recently reported that temporary mounts can be satisfactorily made if the prolonged treatments with alum potassium dichromate and ammonium molybdate are omitted. Specimens prepared in this manner are examined in water. Kirby reports that striking results are obtained with *Euplotes*

The principle of progressive staining by slow diffusion was used by Noland(9) who combined a phenol-formaldehyde fixative with gentian violet. A small amount of Noland's solution added to a wet mount fixes organisms with a minimum of distortion, and the gentian violet diffuses into the cytoplasm slowly, stain-

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* Contribution No. 674 From the Woods Hole Oceanographic Institution.

ing the external structures first. It is possible to regulate the rate of diffusion so that cilia, cirri, and membranelles are temporarily differentiated and may be observed before the background obscures them. Noland's technic is suitable for both flagellates and ciliates but is limited in its application by the short time during which the external structures are visible.

A method of separating specimens from Noland's solution has been devised by displacing the solution with glycerine at the instant when the external structures become stained. The technic not only prevents the staining of the cytoplasmic background but clears it as well. Additional differentiation of the stained structures is obtained by precipitating the dye within them with iodine. The reagents are Noland's solution and iodized glycerine. The formula for Noland's solution is as follows:

80 cc. saturated solution of phenol in water
20 cc. 40% formaldehyde in water
4 cc. glycerine
20 mg. gentian violet

Iodized glycerine is made by mixing two parts of glycerine with one of strong aqueous iodine solution. The latter is made by dissolving crystalline iodine in distilled water containing a small amount of potassium iodide. The amounts are not critical as long as the final solution contains approximately two-thirds glycerine and enough iodine to give it a deep amber color.

A single specimen is first fixed and stained with Noland's solution in a depression slide under a low power binocular microscope where the progress of the staining can be observed. The drop containing the specimen must be small and the concavity flooded rapidly with an excess of Noland's solution. The organism is fixed instantaneously, but the gentian violet is prevented from reaching it by the inhibitory action of the culture medium which rounds up into a spherical droplet with the specimen in the center. Mixing takes place at the surface of the droplet and it diminishes in size forming a shell-like envelope around the specimen. As soon as the dye is observed to reach the surface of the specimen a large drop of iodized glycerine is added from some distance above the preparation to displace the Noland's solution and envelope the specimen. The specimen is then withdrawn with a fine pipette and placed in a second depression slide containing iodized glycerine. The specimen may then be mounted under a coverslip or examined in a hanging drop. It is essential to use iodized glycerine as a mounting medium to prevent rapid fading of the stain.

Specimens prepared by this technic are temporary, but the structures retain the stain for as long as 24 hours. Cirri and membranelles are stained jet black and stand out sharply against a cleared amber background. Exact counts of the fine cirri in the long rows of *Urostyla* are easily made and the intricate patterns of the more complex species can be determined without difficulty. Individual organisms may be selected from wild cultures without the necessity of waiting for mass cultures to develop from isolated specimens. Preparations illustrating the stages in reorganization accompanying fission in *Stylonichia mytilus* make a spectacular classroom demonstration that can be set up in half an hour or less.

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Contribution No. 676

New evidence that migrating gas bubbles, probably the swimbladders of fish, are largely responsible for scattering layers on the continental rise south of New England

PROBLEMS in scattering layer research were discussed at the Woods Hole Oceanographic Institution in a series of weekly meetings during the summer of 1953 by staff members and other interested scientists. Among the methods suggested for identifying components of scattering layers one appeared immediately applicable for testing the hypothesis that fishes with swimbladders are important constituents of some layers. Mr. A. C. VINE proposed that acoustical records be examined for the shifts in resonant frequency of scattered sound that should be observed as swimbladders contract and expand during vertical migrations.

Data for this examination were recorded from the R/V *Bear* on the 23rd and 24th of August, 1953 at 39°42′N, 70°20′W on the continental rise south of New England where the water depth was about 1,100 fathoms. Recordings were made roughly every three minutes for 1 and ½ hours starting ½ hour before dawn and using techniques essentially similar to those described by HERSEY, JOHNSON and DAVIS (1952). These employ an explosion as a sound source and a directional receiver pointing downward. The sounds received in the present work were recorded on magnetic tape through an electronic system having flat response from 50 to 15,000 cps, and were analyzed on a Kay Electric Company Vibralyzer following the " visible speech " techniques described by KOENIG, DUNN and LACY (1946). By reproducing the tape recorded sounds at one-fourth the original tape transport speed analyses covering the full range of the original recording were obtained. The Vibralyzer records are three dimensional displays of the scattered sound in which frequency and travel time of the sound are the two plane coordinates and relative intensity is shown by relative blackening of the teledeltos paper on which the Vibralyzer records, thus giving a plot of sound scattering as a function of depth and frequency when due allowance is made for the directional properties of the receiver.

Analysis of these recordings confirmed the earlier findings of HERSEY, JOHNSON and DAVIS (1952) that there are several scattering layers having peaks of scattering power at different frequencies. They showed further that the peak frequencies increase as the layers descend at dawn in a manner roughly proportional to the first power of the depth. So sensitive a variation with depth suggests a highly compressible scatterer such as a gas bubble. The analysis is too crude to distinguish between the first power of the depth and the 5/6th power, which would be the manner in which the peak frequency of a migrating gas bubble would vary with the hydrostatic pressure. On the assumption that this constituted good enough agreement with the gas bubble theory, we computed the diameter and volume of the corresponding gas bubbles at one atmosphere for the three most prominent peaks. These are 16·7, 5·5, and 1·9 millimetres and 4,700, 165, and 6·5 mm^3 respectively. The first two can be identified with layers that have midday depths of approximately 400 and 300 metres respectively. The midday depth of the third is unknown because its frequency increases to some point beyond the upper limit of our recorders. This occurs rather early in the migration period when its depth is about 180 metres.

This range of sizes falls within those given by MARSHALL (1951) for the swimbladders of common bathypelagic fishes. The 6·5 mm^3 volume agrees rather closely with those reported for *Myctophidae* (lanternfishes). For instance, choosing the commonest lanternfish collected by the *Blue Dolphin* in the same area for which evidence of extended vertical migration was shown (*Diaphus dofleini* Zugmayer), a volume of 11·1 mm^3 is computed for its swimbladder using the dimensions given by MARSHALL for this species. The length of MARHSALL's specimen approximated the mean length of our material. The evidence thus suggests that scattering peaks observed in this area are due to the swimbladders of fishes and that the sea level volume of their swimbladders are approximately given by the gas bubble volumes above. In making this suggestion we are disregarding the departure of the swimbladder from a spherical shape since its shape under the conditions of observation is unknown. We also disregard for the present questions of the size distribution in the population causing a single scattering peak. The collections of the *Blue Dolphin* in this area include many fishes larger than lanternfishes (mainly bathypelagic eels and stomiatids) not yet examined which may have swimbladders of a volume the order of 165 mm^3. The gear used was not appropriate for collecting fishes of such size that their swimbladders would approximate the greatest volume computed, 4,700 mm^3.

The scattering layers in this area have long been known as strikingly more intense than in many other parts of the western North Atlantic, and it is evident that the scattering peaks that have just been described do not comprise all the sound scattered by material in the water. Hence these results are a strong indication that migrating gas bubbles, probably the swimbladders of fishes, are responsible for a large part of the sound scattering in this area, but any suggestion that they are the sole cause of the deep scattering layers is unwarranted.

We are indebted to Miss CONSTANCE HINDLE for carrying out the Vibralyzer analyses and to the several members of the field party who assisted in the observations. This work was carried out under contract NObsr-43270 with the Bureau of Ships, U.S. Navy Department.

Woods Hole Oceanographic Institution J. B. HERSEY
February 18, 1954 R. H. BACKUS

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B. Haurwitz:

The Occurrence of Internal Tides in the Ocean.

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(New York University and Woods Hole Oceanographic Institution.)

The Occurrence of Internal Tides in the Ocean*.

By

B. Haurwitz.

With 3 Figures.

Abstract. A brief introductory discussion is given of the importance of internal waves for theoretical and applied oceanography. The temperature series obtained at four oceanographic stations in the North Atlantic are subjected to harmonic analysis and to the expectancy test in order to determine the possible presence of periodic variations coinciding with the length of the principal lunar semidiurnal tide. Only in one case is it possible to regard the computed harmonic coefficients as representative of tidal effects, with a reasonable degree of assurance while in the other three cases any possible tidal effects are either more or less strongly obscured by random variations or absent. Because of the shortness of the existing oceanographic series a completely satisfactory decision concerning the presence or absence of significant variations of tidal character in the observations is impossible. It is pointed out that oceanographic serial observations of longer duration made simultaneously at different stations would lead to substantial progress in the study of internal waves.

Zusammenfassung. In einer kurzen Einführung wird die Bedeutung der internen Wellen für die theoretische und die angewandte Ozeanographie besprochen. Die im Nordatlantischen Ozean an vier Stationen erhaltenen Temperaturserien wurden harmonisch analysiert und mittels der Expektanzmethode untersucht, um das Vorhandensein periodischer Schwankungen zu bestimmen, die die Länge der wichtigsten halbtägigen Mond-Tide haben. Nur in einem Falle können die berechneten harmonischen Koeffizienten mit genügender Sicherheit als durch Gezeitenvorgänge hervorgebracht angesehen werden, während in den anderen drei Fällen die möglichen Gezeiteneffekte entweder fehlen oder mehr oder weniger stark durch Zufallsschwankungen verdeckt sind. Wegen der kurzen Dauer der vorhandenen ozeanographischen Beobachtungsreihen ist es unmöglich, eine befriedigende Entscheidung darüber

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zu treffen, ob Schwankungen von Gezeitencharakter in den Beobachtungen vorhanden sind. Längere ozeanographische Beobachtungsreihen, die gleichzeitig an verschiedenen Stationen angestellt werden, könnten das Studium der internen Wellen sehr wesentlich fördern.

Résumé. Dans une courte introduction, l'auteur discute l'importance qu'ont les vagues internes pour l'océanographie théorique et pratique. Les séries de température obtenues dans quatre stations de l'Atlantique-Nord ont été soumises à l'analyse harmonique et à la «méthode d'expectance», afin de déterminer la présence possible de variations périodiques ayant la longueur des principales marées lunaires semi-diurnes. Les coefficients harmoniques d'une seule station peuvent être considérés comme suffisamment sûrs pour relever du phénomène des marées, tandis que dans les trois autres cas les effets de marée possibles manquent ou sont plus ou moins fortement voilés par des variations accidentelles. Vu la courte durée des dites séries océanographiques, il est impossible de décider clairement si les observations contiennent des variations dues aux marées. Des séries d'observations océanographiques plus longues, effectuées simultanément à différentes stations, seraient aptes à pousser bien en avant l'étude des vagues internes.

I. Introduction.

Internal waves in the ocean have received considerable attention in recent years, largely thanks to the important contributions to this subject which have been made by Prof. A. DEFANT. Therefore, it seems fitting to discuss this problem in a volume dedicated to Prof. DEFANT.

Apart from the intrinsic interest which internal waves deserve it can be surmised that they play an appreciable role in furthering mixing processes in those regions of the ocean where they occur. This has become especially apparent after DEFANT (1948) has made it very probable that they are, at least in the regions of the continental shelfs, subject to breaking, like the waves at the ocean surface in shoaling water. Further, it is necessary for oceanographic surveys to know if internal waves are present in order to eliminate the effects of such waves on the analysis and interpretation of the data. The importance of such a correction has been demonstrated very convincingly by DEFANT (1950) a few years ago. The effect of ocean surface waves on ship motions is well known and does not need any further elaboration. The "dead-water" phenomenon caused by internal waves generated by the motion of ships has also been fully described in textbooks, for instance by SVERDRUP and Coll. (1942). In a similar, but much stronger way, submarine navigation may be affected by internal waves at greater depths. And it appears that submarines have encountered such internal waves, with rather unpleasant results.

As far as the excitation of internal waves is concerned it can be surmised that they are in part due to atmospheric causes, like the ocean surface waves. Other internal waves may be caused by seismic activity, but in view of the relatively infrequent occurrence of earthquakes, as compared to the apparently quite frequent occurrence of internal waves, it is necessary to attribute the origin of at least many of the observed internal waves to other causes.

One of the most important forces producing periodic changes in the oceans is the tidal action of the moon and the sun. Therefore particular attention has been given to oscillations of tidal periods in the study of internal ocean waves. The present paper will deal with such oscillations of tidal character, especially with the semidiurnal lunar tide.

In order to determine the presence or absence of internal waves in the ocean at a given location and during a certain time interval the observed oceanographic parameters, currents, temperature, or salinity have to be subjected to a harmonic analysis. Such an analysis gives for the assumed period an amplitude and phase constant. But even though the tidal forces act continuously it can not a priori be assumed that the amplitudes and phase constants determined by harmonic analysis are really representative of the effects of tidal action. The latter effects may be so small that they are completely overshadowed by random variations so that the results of the harmonic analysis represent merely the effects of random variations. Hence a statistical test is required to judge the significance of the computed harmonic coefficients, in other words to ascertain whether the coefficients obtained by a purely formal procedure represent the results of tidal action or merely of random fluctuations.

It is the purpose of this paper to show that in some instances the existence of discernible internal oscillations of tidal character is confirmed by the statistical test; in other cases, not. The investigation whose results are being reported here has been conducted at the Woods Hole Oceanographic Institution during the summers of 1952 and 1953 (HAURWITZ, 1952, 1953).

Four oceanographic series have been analyzed. They are summarized in Table I.

The longest of these series was obtained during cruise 77 of the research vessel Atlantis of the Woods Hole Oceanographic Institution when the ship was anchored from 16 to 29 June, 1938 at 34.1° N, 65.9° W, north of Bermuda (Atlantis Station 3091). During this period temperature observations were made every $1^1/_2$ to 2 hours to a depth of more than 1000 m. A brief report

Table I. *List of Oceanographic Series.*

Designation	Location	Duration	No. of Tidal periods	Reference
Atlantis Station 3091	34.1° N 65.9° W	16–29 June 1938	21	Woods Hole data file
Meteor Station 385	16.8° N 46.3° W	12–14 February 1938	4	v. SCHUBERT (1944)
Meteor Station 438	30.0° N 43.8° W	26–28 April 1938	4	v. SCHUBERT (1944)
Altair Station	44.5° N 34.0° W	16–20 June 1938	7	A. DEFANT (1940a)

on this long oceanographic series was published by SEIWELL (1939) who demonstrated the great vertical displacements indicated by these observations.

The other three series of data are those obtained by the German North Atlantic Expedition with the Meteor in 1937 and 1938 (VON SCHUBERT, 1944) and by the International Gulfstream Investigation with the Altair 1938 (DEFANT, 1940a) which were readily accessible to the author. The analysis has in every case been confined to the temperature. In the case of the Atlantis series this was the only oceanographic parameter available. For the other three series salinity and current measurements were also available. But these latter data were not analyzed since the results of the temperature analyses alone give a sufficiently clear picture of the occurrence or absence of internal tides in the data.

The theory of internal waves, and especially of internal tidal waves, will not be discussed here. Reference may be made to a paper by FJELDSTAD (1933) in which the internal wave motions possible in a stratified medium have been studied and in which a numerical method has been developed for the computation of the possible internal waves in an ocean with arbitrary density distribution. An application of this theory to observations of internal tides in a Norwegian Fjord was given by the same author (FJELDSTAD, 1952). Some further theoretical work was done by GROEN (1938) who studied internal waves in a fluid with a certain specified density distribution, characterized by a rather rapid change in an intermediate layer and almost constant density in two very deep layers above and below the intermediate layer.

It is apparent from this theoretical work as well as on general grounds that for more complete information about internal waves simultaneous observations from more than one location are desirable. Such observations have been obtained by FJELDSTAD in the paper referred to previously (1952), and by NEUMANN (1949) as part of an investigation of oscillations with periods considerably shorter than the tidal periods. But from the open ocean comparable data have not been available at the time when this investigation was made. Simultaneous observations at three locations would permit one to obtain information about the wave length of the oscillation, about its lateral extent, and about the direction of travel if the wave is in fact progressive. Because of the absence of such observations attention must here necessarily be confined to the variations at one locality.

II. Statistical Procedure.

The numerical procedure for studying the four series of observations and for evaluating the significance of the computed amplitudes of the semidiurnal lunar internal tide will be reviewed only briefly in order to establish the terminology used here and in order to make some comments pertinent to our specific problem. For a thorough discussion of the statistical method employed reference may be made to books dealing with statistical methods, for instance CHAPMAN and BARTELS (1940), STUMPFF (1940), CONRAD and POLLAK (1950).

A set of data which is suspected of showing a period of a certain length can be subjected to a harmonic analysis according to well-known methods. As a result one will obtain an expression, or a sum of expressions, of the form

$$a_n \cos n\, t + b_n \sin n\, t, \tag{2.1}$$

Here t is the independent variable, for instance the time, expressed in angular measure, n an integer representing the frequency, and a_n and b_n the harmonic coefficients. An alternate form of the foregoing expression is

$$A_n \cos (n\, t - \alpha_n) \tag{2.2}$$

where the amplitude

$$A_n = \sqrt{a_n^2 + b_n^2} \tag{2.3}$$

and the phase constant

$$\tan \alpha_n = \frac{b_n}{a_n}. \tag{2.4}$$

Since it is always possible to represent a set of data by a series of terms of the form (2.1) or its alternate (2.2) the harmonic analysis does not prove anything about the reality of the suspected periods. Even a set of random numbers can be represented by a harmonic series.

In the case under investigation one may argue that it is likely that the oceanographic parameters show variations with the tidal periods because of the continued action of the tidal forces. However, as already pointed out in the introduction, the amplitudes computed by the harmonic analysis do not necessarily represent the effects of tidal action since these effects may be completely obscured by other influences. Hence a statistical test is required to evaluate the significance of the computed amplitudes.

Such a test is provided by the expectancy method. The expectance is a measure for the amplitude A_n of a harmonic component to be expected in random data. Statistical theory shows what the probability is that the actual amplitude exceeds the expectance by a certain amount. Evidently if this probability is very small it is unlikely that the computed amplitude is due to random data, or in other words, it is likely that the period exists in the analyzed data.

The expectance is given by the following expression

$$E^* = 2\, \mu / \sqrt{n},$$

where μ is the standard deviation of the individual n numbers. It can be shown that the probability that any amplitude exceeds $k\, E^*$ is given by

$$p = e^{-k^2}.$$

The application of this expectance criterion is, however, restricted to those cases where the individual members of the set of numbers are independent from each other. This is true for random numbers, but not for the majority of geophysical time series which have a certain degree of "conservation". In the cases to be considered here, for instance, the subsequent heights of the isothermal surfaces will have a certain autocorrelation since large positive deviations from the mean value are more likely to be followed by other large positive deviations than by large negative ones.

It is possible to avoid or at least to reduce greatly the effects of the autocorrelation by introducing instead of the expectance a somewhat different expression, the *expectancy.* In order to determine this quantity let the whole analysis interval $t_1 - t_0$ be an integral multiple of the period T which is being studied,

$$t_1 - t_0 = s \cdot T.$$

This can always be arranged by a suitable choice of the end points t_1 and t_0. The total interval is now subdivided into equal parts each of which is either equal to the period T or to a multiple of T. The harmonic coefficients $a_n^{(i)}$ and $b_n^{(i)}$ are then determined separately for each partial interval of which there may be r, say, where $r \leq s$. Let

$$A_n^{(i)2} = a_n^{(i)2} + b_n^{(i)2},$$

the amplitude for each partial interval. The determination of the different $A_n^{(i)}$ is based on a set of data which with the exception of the last points of one partial interval and the first points of the next partial interval are far enough apart so that the effect of any autocorrelation in the data is at least greatly reduced. Therefore, it can be assumed that the $A_n^{(i)}$ determined for the different partial intervals would in the absence of the suspected periodicity behave like random numbers and scatter around a mean value which may be assumed zero a priori. The harmonic coefficients $a_n^{(i)}$ and $b_n^{(i)}$ can be considered as the components of a vector which may be plotted in a coordinate system with a_n and b_n as the horizontal and vertical axes, respectively. This representation is the well-known harmonic dial.

The quadratic mean value of the lengths of the vectors which represent the harmonic coefficients of the individual partial intervals is called the *expectancy* of these individual vectors,

$$e^2 = \sum_{i=1}^{r} A_n^{(i)2}/r.$$

It is convenient to introduce the expectancy E for the distance of the center of gravity of the cloud of r points $a_n^{(i)}$, $b_n^{(i)}$ from origin,

$$E^2 = \frac{e^2}{r} = \frac{1}{r^2} \sum_{i=1}^{r} A_n^{(i)2} \tag{2.5}$$

The distance of the center of gravity of the point cloud from the origin is given by

$$\bar{A}_n^{\,2} = \frac{1}{r^2}\left(\sum_{i=1}^{r} a_n^{(i)}\right)^2 + \frac{1}{r^2}\left(\sum_{i=1}^{r} b_n^{(i)}\right)^2 \tag{2.6}$$

and the probability that

$$\bar{A}_n = kE \tag{2.7}$$

is

$$p = e^{-k^2} \tag{2.8}$$

for random data. Hence if the probability p is small it is likely that the data are not randomly distributed, but that the suspected period is real.

The derivations leading to the foregoing formulae presuppose that the number of intervals, r, on which the test is based is not too small. This can be seen directly if the following case is considered.

Suppose that the $a_n^{(i)}$ and the $b_n^{(i)}$ for all partial intervals are the same and that the amplitude for each partial interval is A_n. In this case $p = e^{-r}$. If $r = 2$, for instance, the probability is one in seven that any amplitudes, even though they are the same for both partial intervals, are due to random data. The expectancy test is, of course, not applicable to so few data, and the example merely illustrated this point. We shall, however, have to apply it later to data where $r = 4$ and where therefore the lowest probability is one in 55 that the amplitudes found by the harmonic are due to random data. Also in this case the application of the test can only be justified because longer series are not available.

Apart from the property of conservation for which allowance can be made in our expectancy tests, as described above, geophysical time series also have frequently the property of "quasi-persistence". This property may be described as a tendency for certain similarities to recur in subsequent analysis intervals, although with diminishing intensity. When the total time series to be analyzed is sufficiently long the degree of quasi-persistence can be determined and allowed for in the expectancy test. However, the oceanographic series available for the present investigation are not long enough to do so. It will be noted that quasi-persistence increases the expectancy. Therefore the probabilities given below that the computed amplitudes of internal tides are due to chance may be too low. This fact would not modify our later conclusions in cases where the amplitudes are evidently due to random effects. But in the cases when the probability of random effects is small it will be necessary to keep in mind that this probability would increase if the series possesses quasi-persistence.

Another point to be mentioned here concerns the exact length of the period whose occurrence is to be tested. If a sufficiently long series of observations is available the choice of a period slightly different from the exact one would manifest itself in a systematic change of the phase constant as each consecutive partial interval is analyzed. But in a short series comprising only a few periods this variation of the phase constant would be completely obscured by the irregular changes due to superimposed random fluctuations in the data.

In the particular problem studied here this difficulty arises because of the slight difference between the period $T_e = 12.42$ hours of the principal lunar tide and the period $T = 12$ hours of the principal solar tide. While the former is as a rule the dominant one at the ocean surface this is not always true, and it can therefore not definitely be ascertained from a short series of observations which of the two periods is correct, even if the expectancy test is positive. In the subsequent discussions of the results of the analyses it is necessary to keep this limitation also in mind, even though it will not be repeated in each case specifically that the actual period of oscillation may differ from the principal lunar tidal period, 12.42 hours.

III. Analysis of the Data.

A summary of the oceanographic series which were studied has been given in Table I above (see p. 408). The average vertical density distributions as obtained from observations made at these stations are shown in Fig. 1. In the case of the Atlantis and the Meteor observations one series of measurements was extended to much greater depths. The results of these deep soundings are indicated by individual points not connected by a continuous curve. In the upper layers where mean values from the serial observations are also available the observations of the single deep sounding agree very well with the means of the serial observations. The average depth during each station is indicated by the horizontal line at the bottom of each diagram in meters. In the case of the

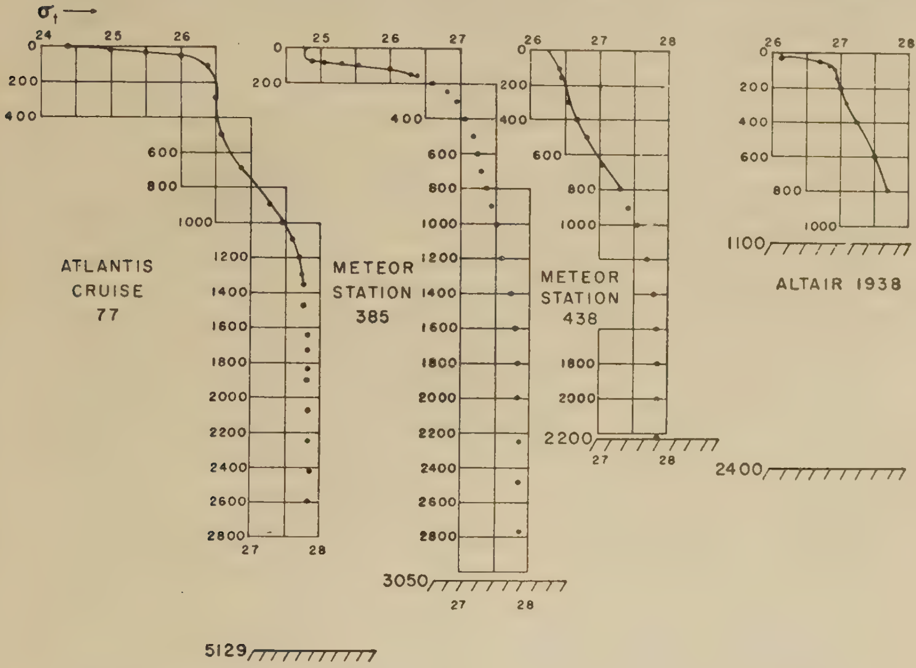

Fig. 1. Vertical distribution of the density; $\sigma = (\varrho - 1)\,10^3$ where ϱ = density in gm/cm^3.

Altair where the depth varied because the ship anchored over a seamount the greatest and smallest depths are shown.

The vertical density distribution during the Atlantis station shows a very rapid density increase downward in the uppermost 100 meters, followed by a more homogeneous layer. Between 500 and 1200 m the density gradient is again slightly larger. Similarly, the Meteor station 385 and the Altair station show a surface layer of large density gradient followed by a more homogeneous layer. At Meteor station 385 the density at the sea surface is slightly higher than in the shallow homogeneous layer right below it. At Meteor station 438 the density gradient in the highest layers is much less strong than at the other stations and considerably more uniform through the first 1000 m. The temperature distribution resembles the distribution of the density closely in all cases.

a) Atlantis Station 3091

The data for the study of this series were available in the form of a cross section showing the depths of the various isothermal surfaces as functions of the time. The height variations of the 18° C, 15° C, and 10° C isotherms were analyzed. Depths were read off the cross section at time intervals of 2 hours and 4.2 minutes, corresponding to two average lunar hours. The first reading was taken on 16 June, 2200 AST (Atlantic Standard Time, 60° W longitude), the last one to be used in the following analysis on 27 June, 1702 AST, giving altogether 21 lunar semidiurnal tidal periods. The expression for the lunar semidiurnal tidal oscillation is assumed in the form (2.1) with $n = 2$ where t is the lunar time, reckoned from an arbitrary zero et 16 June 1938, 2200 AST. This zero time corresponds approximately to 0630 local lunar time at the Atlantis' position.

The determination of the harmonic coefficients a_2 and b_2 was made for 7 groups of data, each consisting of three consecutive semidiurnal tidal periods. These coefficients are not reproduced here. They can be found in a Technical Report (HAURWITZ, 1952) of the Woods Hole Oceanographic Institution. With the aid of these coefficients the expectancy E and the mean amplitude $\overline{A}_n$ were computed according to equations (2.5) and (2.6). These quantities, their ratio k, and the probability p that the amplitudes are due to random variations are shown in Table II. The last line gives the mean depth of each isotherm. It will be seen that the probability of randomness is quite large. Therefore, the amplitudes $\overline{A}_n$ cannot be regarded as due to tidal effects.

Table II. *Expectancy Test fôr Semidiurnal Lunar Tides. Atlantis Station 3091.*

Isotherm	18° C	15° C	10° C
$\overline{A}_n$	4.66 m	4.05 m	2.61 m
E	4.10 m	3.29 m	2.20 m
p	0.28	0.22	0.24
Mean depth	175 m	630 m	870 m

During the observation period gradual unperiodic variations of the depths of the various isothermal surfaces took place. An attempt was made to eliminate the effects of these variations before making the harmonic analysis. But since the probability of randomness obtained when such a correction is applied is not substantially smaller than that given in Table II it needs not be discussed here.

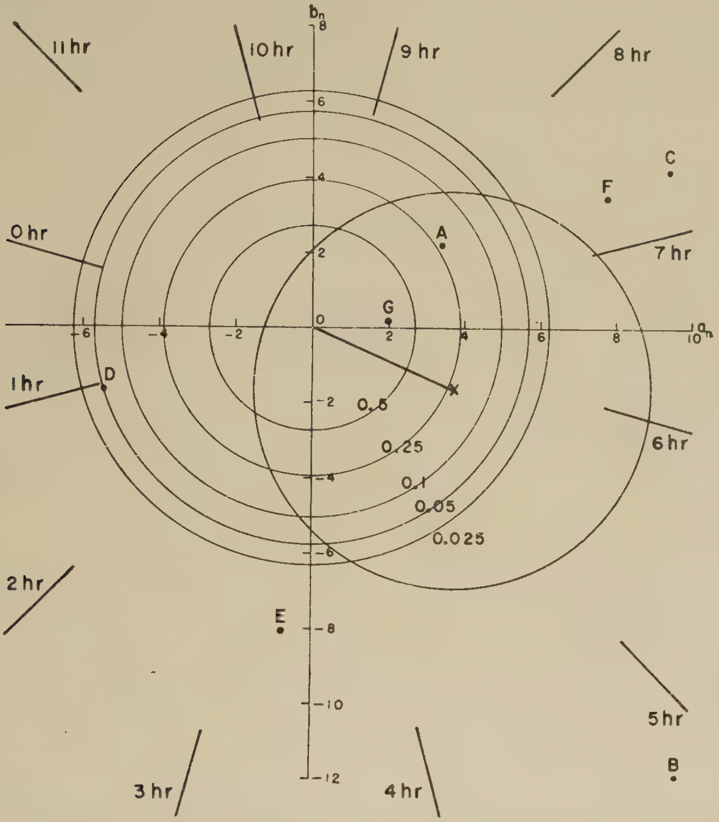

Fig. 2. Harmonic dial for the lunar semidiurnal oscillation of the 15° C isotherm. Atlantis cruise 77. Units in meters.

For the 15° C isotherm the results of the expectancy test are also shown in a harmonic dial, Fig. 2, where the harmonic coefficients a_n and b_n are the abscissa and ordinate of a Cartesian coordinate system. On the margin of the figure the local lunar time of the occurrence of the maximum for given values of a_n and b_n is indicated. Because of our choice of the direction of the a_n and b_n axes the time increases in counter-clockwise direction, opposite to the more conventional clock faces. The points A through G represent the harmonic coefficients for each of the seven partial analysis periods. The figure contains further five concentric circles around the origin which represent lines of equal probability that a mean amplitude $\overline{A}_n$ of the same magnitude as each radius is due to random data. The position of $\overline{A}_n$, the mean of the seven points A through G, is marked by the cross connected with the origin of the coordinate system.

The results of the analyses of the individual 7 groups, represented by the points A through G, scatter widely. In order to have a measure of this scatter the deviations $\Delta a_n^{(i)}$ and $\Delta b_n^{(i)}$ of the individual $a_n^{(i)}$ and $b_n^{(i)}$ from the mean have been formed. From these deviations the quantity

$$0.83 \sqrt{\frac{1}{r} \left[\Sigma (\Delta a_n^{(i)})^2 + \Sigma (\Delta b_n^{(i)})^2\right]}$$

has been computed. The resulting number may be considered as the probable error of $A^{(i)}{}_n$. Its magnitude, 6.4 m, is indicated by the circle around the endpoint of $\overline{A}_n$ as the center. (The radius of this circle as shown in Fig. 1 should be increased by 20%.)

Since the Atlantis series comprises approximately ten days it was also subjected to a search for the longer tidal periods, namely of about one day's length. At the same time the higher harmonics were included in the computations since some of these shorter-period oscillations have occasionally also been found in surface data. No attempt has been made to distinguish between the three diurnal partial tides, namely the lunar-solar tide of 23 hours 56 minutes, the principal lunar tide of 25 hours 50 minutes, and the principal solar tide of 24 hours 4 minutes. The time interval of 24 lunar hours was taken as the basic analysis interval.

Only the depth changes of the 18° C isotherm were analyzed since the study of the lunar semi-diurnal tide indicated no striking differences between the behavior of this isotherm and the 15° C and 10° C isotherms. As before, values at two-hourly (lunar) intervals were used beginning again with the reading on 16 June, 2200 AST. The observations were arranged into five groups each comprising two lunar days, and the harmonic analysis was performed separately for each of these groups. The harmonic coefficients obtained by this analysis are not reproduced here (see HAURWITZ, 1952), but the data for the expectancy test are shown in Table III. It will be seen that the amplitudes $\overline{A}_n$ computed for the various periods are not significantly higher than what could be expectey in random data. The only period with appreciably lower probabilitd

Table III. *Expectancy Test for Lunar Tides Atlantis Station 3091. Isotherm 18° C.*

Period	24	12	8	6	4.8 lunar hours
$\overline{A}_n$	5.15	5.02	3.34	5.17	0.76 meters
E	6.66	4.24	3.47	3.12	2.12 meters
p	0.55	0.24	0.39	0.064	0.88

than the others is the six-hourly one which would occur once in about 16 random samples. However, even this probability is not particularly low. An additional reason for not regarding the six-hourly period as significant is based on the consideration that no such period exists in the tidal potential. Under certain conditions six-hourly tidal oscillations may occur, especially in shallow or confined waters. But in view of the rather small likelihood that this oscillation as found in the present data is anything but a random effect it seems futile to speculate here on its possible physical origin in the deep ocean.

The lunar diurnal equilibrium tide depends on sin $2d$ where d is the moon's declination. This expression undergoes considerable changes during the analysis interval. However, an inspection of the amplitudes of the 24-hourly term for the individual partial analysis intervals failed to show a systematic variation with sin $2d$. Nor did the phase constants show a systematic shift with the sign of sin $2d$. Hence the negative result of the expectancy test cannot be attributed to the effect of the lunar declination.

b) Meteor Station 385.

The location of this station is given in Table I. The serial observations extend only through the uppermost 150 m. Therefore the analysis has to be confined to this layer. As pointed out by von Schubert (1944) an inspection of the figures showing the heights of isothermal and isohaline surfaces as functions of time (his Figures 7 and 8) shows fairly clearly a semidiurnal tidal period. In order to perform the analysis time-cross-sections of the isothermal surfaces 24.5° C, 23° C, 22° C, 21° C, and 20° C were drawn on the basis of the published soundings, and values of the heights of these surfaces were read off for each lunar hour beginning with 0100 local lunar time, corresponding to 12 February 1938, 11:15 45° W meridian time. Altogether, hourly soundings were taken for 60 solar hours, but because of the greater length of the lunar hour only four semidiurnal lunar tidal periods were available. The harmonic analysis was performed separately for each individual tidal period. The harmonic coefficients have been reproduced elsewhere (see Haurwitz, 1953).

From the harmonic coefficients the mean amplitude A_n, its expectancy E, and the probability p, that $\overline{A}_n$ is due to random data have been computed. They are given in Table IV which also shows the mean depth of each isotherm. The main conclusion to be drawn from this table is that it is not very probable that the amplitudes of the semidiurnal oscillation as computed are due to random data, in other words that the existence of semidiurnal internal tide is very probable. The value of the probability p that the amplitude $\overline{A}_n$ is due to random data is between 0.02 and 0.03 for the different isothermal surfaces. This probability for randomness is not very small, especially if the possibility of quasi-persistence is considered, but it should be remembered that with only four groups of data the lowest probability which the expectancy test could give is $e^{-4} = 0.018$.

Table IV. *Expectancy Test for the Lunar Semidiurnal Tide. Meteor Station 385.*

Isotherm	24.5° C	23° C	22° C	21° C	20° C
$\overline{A}_n$	11.2 m	13.5	14.4	13.9	11.8
E	5.7 m	6.9	7.4	7.5	6.3
p	0.02	0.02	0.02	0.03	0.03
Mean depth	78 m	95	106	116	129

For the 23° C isotherm a harmonic dial similar to Fig. 2 for the Atlantis data is shown in Fig. 3. A comparison of the two figures shows clearly how much more probable the existence of the semi-diurnal lunar tide is in the data from the Meteor Station 385 than in the Atlantis data. The small circle around the center of gravity of the four points A through D shows the probable error of $\overline{A}_n$. The radius of this circle should be increased by 20%.

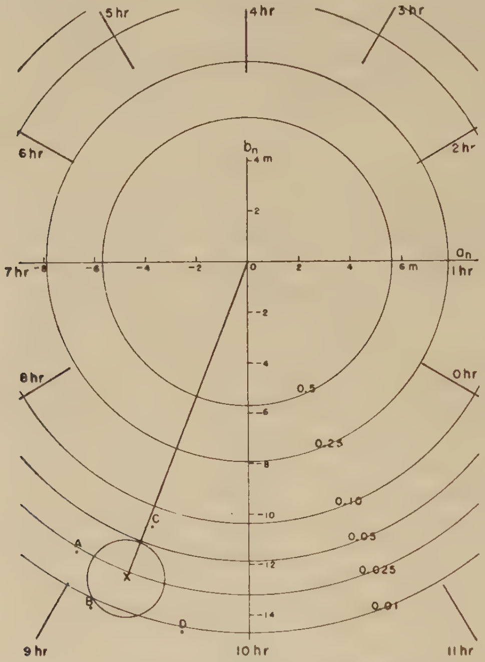

Fig. 3. Harmonic dial for the lunar semidiurnal oscillation of the 23° C isotherm. Meteor station 385. Units in meters.

At smaller depths than about 80 m, the mean depth of the 24.5° C isotherm, tidal oscillations could not be observed, as has been mentioned already by VON SCHUBERT (1944), because the vertical gradients of temperature and salinity are very small.

As Table IV shows the amplitudes increase downwards and reach a maximum for the 22° C isotherm, but the differences are not larger than the probable errors. Hence, it must be concluded that no significant variations with depth of the internal tidal oscillation can be found. Since the layer from which data are available comprises only 50 m this is not surprising.

As pointed out in section 2 it is not possible to decide on the basis of the short series of available data whether the period length is really equal to that of the principal lunar semidiurnal tide. In order to illustrate this difficulty a harmonic analysis was performed with the principal solar semidiurnal tidal period as the analysis interval. For this analysis not the height of an isothermal surface was chosen, but the temperature variation at 120 m depth which could be taken directly from von Schubert's (1944) tables. Since the whole series comprises 60 hours five individual periods are available for the expectancy test. The probability that the mean amplitude obtained for this level, 0.97° C is due to random fluctuations is 0.02. This figure is slightly smaller than the probability, 0.03, that the lunar-tidal harmonic coefficients of the 21° C and 20° C isotherms are due to random fluctuations. But because of the short length of the series of observations the slight difference between these probabilities is not significant.

In order to demonstrate that, on the other hand, the expectancy test shows the non-existence of periods whose lengths differ substantially from the real ones the temperature variations at 120 m depths were also analyzed for a period of eight hours. The expectancy test showed that the resulting mean amplitude of 0.14° C would occur in random data with the probability 0.79. Hence such a period does not exist in the data.

c) Meteor Station 438.

The location of this station is shown in Table I. According to Figure 1 there is no layer of very rapid density increase near the surface as at the two preceding stations. But a pronounced density gradient exists throughout the highest 800 m to which depth the regular serial observations were made. As at the other Meteor Station observations were made at hourly intervals, from 26 April 1938, 10 : 12 45° W meridian time to 28 April 1938, 20 : 58 45° W meridian time, a period of almost 60 hours. Thus, again, four consecutive lunar semidiurnal periods could be analyzed. As zero time, 1400 local lunar time on 26 April was chosen which corresponds to 10 : 46 45° W meridian time. The temperature data published by von Schubert (1944) were used to construct a time-cross-section of the height of various isothermal surfaces, viz., 18.5° C, 18° C, 17.5° C, 17° C, etc. to 10° C from which the height of each surface for every lunar hour could be read. Even a casual inspection of this time cross section showed that internal oscillations of tidal character if present at all are much less well developed than at Meteor Station 385.

The results of the expectancy test for the lunar semidiurnal period are summarized in Table V whose arrangement is the same as Table IV. Except for the 16° C and 14° C isotherms the probability is always greater than one half that the amplitudes found by harmonic analysis are due to random fluctuations. Even for the 16° C and 14° C isotherms the pro-

Table V. *Expectancy Test for the Lunar Semidiurnal Tide. Meteor Station 438.*

Isotherm	18.5° C	17.5° C	16° C	14° C	12° C	10° C
$\overline{A}_n$	3.1 m	1.0	5.0	1.9	1.9	2.4
E	4.0 m	1.5	3.3	1.4	2.9	3.3
p	0.55	0.63	0.11	0.16	0.65	0.58
Mean depth	61 m	220	401	533	652	778

bability of randomness is too large to regard the existence of a semidiurnal oscillation as established.

It may be added that the mean vertical temperature gradient has the following values:

Depth	0—100 m	100—300 m	300—400 m	400—800 m
° C/100 m	.91	.54	1.03	1.56

Hence the local temperature changes from which the height changes of the isothermal surfaces have been computed are very small; even the amplitude of the 16° C isotherm, 5 m, corresponds only to about 0.70° C. The appearance of greater randomness in the variations of the higher isotherms, 18.5° C and 17.5° C, might therefore be attributed to the still smaller lapse rates in these layers. However, if this reasoning were correct the 12° C and 10° C isotherms should also show a lower probability of randomness than they actually do since they are in the layer between 400 and 800 m where the temperature decreases even more rapidly than between 300 and 400 m. It is, of course possible that the existence of an internal tidal oscillation was confined to the vicinity of the 16° C isotherm because of its position near a discontinuity of the temperature lapse rate. But because of the very large value of the probability p that the amplitudes are due to random data rather than an internal tide it does not appear necessary to consider this possibility here in greater detail.

d) Altair Station 1938.

The fourth series of observations was obtained by the Altair during the period from 16 to 20 June 1938 (DEFANT, 1940a). Hourly soundings were made for a period of 87 hours so that 7 complete lunar semidiurnal tidal periods were available. The hourly soundings were made to a depth of 800 m. Instead of determining and analyzing the depths of various isothermal surfaces as in the case of the Meteor data the temperature changes at given levels will here be considered directly following the procedure used by DEFANT (1940b). Further, instead of analyzing separately the temperature data at certain levels the temperature of the following levels have been added and their sums analyzed:

I	25 m	50 m	75 m	
II	100 m	150 m	200 m	
III	300 m	400 m	600 m	800 m

This combination of data has the advantage that it smooths out some of the irregularities in the temperature variations at the individual levels. As pointed out by DEFANT the indicated selection of height combinations follows the actual stratification of the ocean at the Altair station (see Fig. 1) into a surface layer down to 100 m with a sharp discontinuity at the surface, a middle layer of normal density increase to about 350 m and a lower layer with normal density increase separated from the middle layer by a weaker discontinuity layer.

For the analysis of the Altair data according to the lunar semidiurnal tidal period lunar time for Greenwich rather than for the local meridian was used. The origin of the time axis was 09 : 00 lunar Greenwich time corresponding to 17 June 1938, 00 : 02 GMT.

The figures on which the expectancy test is based are given in Table VI.

Table VI. *Expectancy Test for the Lunar Semidiurnal Tide. Altair Station, 1938.*

Layer	I	II	III
$\bar{A}_n$	0.043° C	0.036° C	0.032° C
E	0.054° C	0.022° C	0.021° C
p	0.53	0.06	0.10

The temperature amplitudes are quite small, only of the order of a few hundredth degree Centigrade. In order to show the corresponding magnitude of the vertical displacements the mean vertical temperature gradients must be considered. These are as follows, according to DEFANT (1940b):

Depth m	0	25	50	75	100	200	300	400	600	800
° C/100 m	3.9	5.3	4.2	1.6	1.0	1.2	1.6	1.5	0.7	

For instance since the mean amplitude for layer II is 0.036° C the corresponding amplitude of the vertical oscillation would be less than 4 meters. This value is, of course, computed on the assumption that the temperature variation is entirely due to vertical motion and not to horizontal advection. The latter possibility has been considered by DEFANT.

The probability is very high that the amplitude for the semidiurnal lunar tide computed for the top layer is not significant. The probabilities for the middle and lower layers are considerably smaller, giving greater confidence in the reality of the internal tide at these levels, even though the values of p are not small enough to make the existence of the internal tide here a certainty. But despite the relatively high values of p for these two layers it is remarkable that especially in layer II where the temperature gradients are smallest the probability of randomness is also smallest. This fact suggests that with a longer series of observations the existence of the internal semidiurnal tide would have been brought out by the expectancy test.

From an inspection of the current measurements, and the temperature and salinity soundings DEFANT (1940b) surmised that a 17-hourly wave was superimposed on the semidiurnal lunar tidal oscillation. That an oscillation of 17 hours duration might exist is theoretically plausible since the period of the inertia motion at this latitude is 17 hours. Therefore the Altair observations have also been analyzed with respect to this period. Five complete inertia periods are contained in the time interval during which soundings were made. For the origin of the time axis the same time was chosen as in the case of the analysis for the lunar tidal period; viz., 17 June, 00 : 02 GMT.

The expectancy test is summarized in Table VII. The probability is large that amplitudes of the magnitudes found for the inertia period would occur in random data. Therefore, the reality of the 17-hour period is open to serious doubt.

Table VII. *Expectancy Test for the Inertia Period. Altair Station, 1938.*

Layer	I	II	III
$\bar{A}_n$	0.038° C	0.021° C	0.011° C
E	0.047° C	0.020° C	0.019° C
p	0.53	0.34	0.70

In order to test how well the superposition of the two periods, namely, the lunar semidiurnal and the inertia period, represents the observed data the mean temperature of layer II has been computed by harmonic synthesis for every lunar hour and compared with the observed mean temperature. The correlation coefficient between the 83 computed and observed values is only 0.54, indicating that the representation is not very satisfactory.

The existence of a 17-hour period in the Altair data appears thus unlikely. Nevertheless the possibility of the existence of two superimposed periods in the observation material raises the question as to the influence of the coexistence of two or more periods on the expectancy test. If a sufficiently long series of data is available, the effect of an additional period T_2 on the expectancy test applied to the first period T_1 can be disregarded. For a short series this is no longer true. If the harmonic constants of T_2 are known a correction can be applied to the harmonic constants of T_1 in order to eliminate the effect of T_2, before the expectancy test is performed. But in view of the high probability that no 17-hour period exists in the Altair data the correction formulae will not be given here. It may suffice to say that such a correction was also applied to the probabilities given in Table VI, and that it did not change substantially the figures for p given there.

IV. Conclusions.

The preceding analyses show that internal waves of tidal character appeared with something approaching reasonable certainty only in one case, namely at Meteor station 385. At the other stations the expectancy test gives either inconclusive results or shows that no such oscillations occurred in the observations.

It is apparent from the discussion presented here that only longer series of data, lasting more than just 2 or 3 days, permit a decision as to the existence of significant internal tidal waves, and it is one of the principal aims of this paper to stress the need for such adequate observations. Furthermore, the value of any series of observations will be greatly enhanced if measurements are taken simultaneously at three observation points, as explained in the introduction. Such synoptic observations would not only support each other, but at the same time give much needed information about the wave length and direction of travel of these internal waves and about their lateral extent.

One might raise the question why such internal waves do not appear everywhere in the ocean where gradients of temperature and salinity would permit their observation. Since the lunar tidal potential affects all the water masses its influence should act at every point and at all times. However, it is likely that the stratification of the ocean is not at all times and places suitable for the development of internal waves with tidal periods which have appreciable amplitudes. Until simultaneous observations from more than one point are available the study of the conditions most favorable for the development of internal tidal waves will be seriously impeded. It would be very desirable if such observations would be available so that one could anticipate the occurrence of internal waves from a study of the stratification of the water without having to occupy a particular fixed station for a lengthy time interval. This would be not only of great theoretical interest, but also of great practical importance for the interpretation of oceanographic observations and their representativeness, for underwater navigation, and for the forecasting of sound propagation in the ocean.

The question whether the internal waves discussed here are due to horizontal or vertical motions or to a combination of both is beyond the scope of this paper. Also for a decision on this question observations from three points would be very helpful since they would give the necessary information about the horizontal gradients of the oceanographic parameters involved.

Acknowledgments.

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STUDIES OF THE ELECTRIC POTENTIAL BETWEEN KEY WEST, FLORIDA, AND HAVANA, CUBA

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(Contribution No. 679 of the Woods Hole Oceanographic Institution)

Abstract--The mass transport of the Florida Current across the Key West-Havana section has been studied by means of the associated electrical potential due to the geomagnetic field. An analysis of the seasonal, daily, and short-term variations of the transport is presented, as well as a critical discussion of the limitations of the method of measurement employed.

Introduction

Motion of an electrolyte in the geomagnetic field leads to the development of an induced potential difference at right angles to the direction of motion. It has recently been pointed out [MALKUS and STERN, 1952] that the potential ϕ across a stream is related to the velocity v of the stream by

$$\int_0^d [\phi(\infty, d) - \phi(-\infty, d)]\, dz = \int_0^d \int_{-\infty}^{\infty} H_z\, v\, dx\, dz \quad \ldots\ldots\ldots\ldots (1)$$

If the bottom is flat and nonconducting and the horizontal variation of the Earth's magnetic field is neglected, this reduces to

$$T = Vd/H_z \quad \ldots\ldots\ldots\ldots (2)$$

where T = transport, m^3/sec; V = electrical potential difference, v; d = depth of water, m; and H_z = vertical component of the geomagnetic field, $webers/m^2$.

An analysis for an elliptical sea bed of finite conductivity [LONGUET-HIGGINS, 1949] shows that the effect of sea-bed conductivity is to reduce the potential between the edges of the stream by the factor

$$k = 1/[1 + (w/2d)(\sigma_B/\sigma_S)] \quad \ldots\ldots\ldots\ldots (3)$$

where w = width of stream d = maximum depth, σ_B = electrical conductivity of bed, and σ_S = electrical conductivity of sea water. Application of (2) and (3) makes possible the continuous measurement of the net transport across any section of an ocean current, provided that the potential difference V across the section can be determined by establishing a suitable electrical connection across the stream. The kind cooperation of the Western Union Telegraph Company, which operates communication cables between Key West and Havana (Fig. 1), has made possible such measurements of the Florida Current during the past year.

The magnitude of the correction given by (3) may be estimated using, for the Florida Straits, the values $w = 160$ km, $d = 1.68$ km (maximum depth), $\sigma_B = 5 \times 10^{-5}$ mho/cm, and $\sigma_S = 5 \times 10^{-2}$ mho/cm to obtain $k \approx 0.95$.

Since the estimated correction for the effects of bottom conductivity is so small and its uncertainty so great, it was decided not to apply any systematic correction but to compute the transport directly from the measured potential by (2).

A further difficulty in relating transport to potential lies in the fact that (2) assumes a flat bottom. As long as the major portion of the Florida Current remains over the central portion of the Straits, the use of an effective average depth should be an acceptable approximation. If, however, owing to a meander, the axis should shift over the sloping bottom of the Key West side, erroneously high values of transport may result.

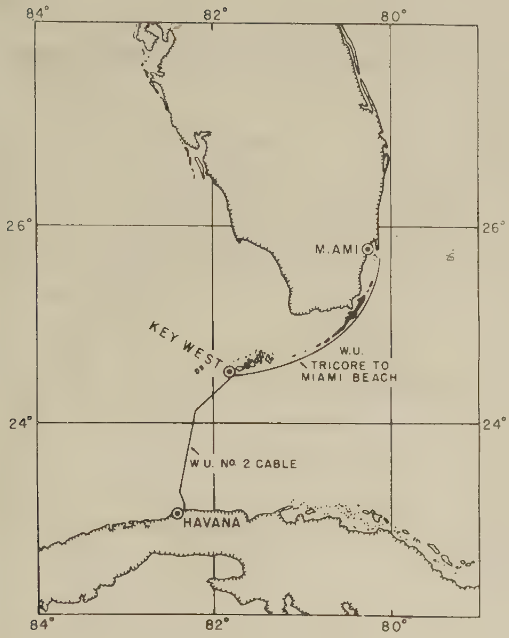

Fig. 1--Cable location

A numerical estimate of the magnitude of this effect was made using the velocity profile obtained by direct current measurements [PILLSBURY, 1887] and an average bottom profile. It was assumed that a shift of the axis of the current may be adequately represented by a rigid translation of the velocity profile. The results show that a meander of ten-km amplitude changes the potential by eight per cent, while a shift of 20 km changes the potential by 20 pct, a shift to the north serving to increase the potential. Little is known about the magnitude of the meanders that actually occur in this region so that the significance of this result cannot be evaluated at this time.

It should also be noted that it is possible to have a potential at right angles to the water motion even though there is no net transport across the section if the bottom is not level. Thus an elongated eddy running east over deep water and west over the shallower water close to Key West will indicate transport to the west even though there is no net transfer of water.

The data are obtained as a continuous curve of potential versus time. This curve exhibits fluctuations which may be divided into a number of categories according to their origin.

A 24-hr record will have the following characteristics: (a) It has an average value which is always positive and represents the average transport during the given interval. A study of the 24-hr averages gives a picture of the seasonal variation in the transport. (b) The data show variations having the tidal period which may be ascribed to the effect of the Atlantic and Gulf tides on the transport through the Florida Straits. (c) If the tidal variations are subtracted from the record, there remain irregular, short-term fluctuations which on some days are wholly absent and on others are greater in amplitude than either the tidal component or the average value. These fluctuations are found to be due to the variations in the horizontal component of the geomagnetic field. (d) Finally, there is noise of small amplitude and short duration which is ascribed to man-made interference. These various aspects of the record will be discussed in the following sections.

Average transport for the year 1952-1953

The average transport of the Florida Current obtained from (2) was 27 × 10^6 m^3/sec for the period August, 1952, to July, 1953. This figure lies well within previous estimates. Direct measurements with a current meter from an anchored ship [PILLSBURY, 1887] gave a transport of 28 × 10^6 m^3/sec. An estimate obtained from a series of dynamic sections [MONTGOMERY, 1941] yielded a transport of 26 to 30 × 10^6 m^3/sec. This agreement between the electrical measurements and previous estimates of transport confirms that the correction for bottom conductivity is small.

The seasonal variation of the transport

A curve of the seasonal variation of the transport of the Florida Current (Fig. 2) is based on 24-hr averages of transport to eliminate the tidal influence. The most striking feature of this curve is the wide range and rapid fluctuation of the transport. For example, early in December, 1952, the transport more than doubled in a period of only three weeks. The range of transport values during the year is almost as large as the average transport for the year, the lowest value being 14 × 10^6 and the highest 39 × 10^6 m^3/sec. These extreme values persisted for only a few days and are considerably outside the range of values previously reported for transport. It is interesting to note that WAGNER and CHEW [1953] have recently reported high values of transport computed from GEK data. These, however, appear to be partially due to tidal transports.

Comparison with tide-gage data--An independent measure of the variation of the current is available in terms of the average surface current which may be obtained from the difference in the tidal height at two stations on either side of the stream by the equation

$$\bar{v} = (h_1 - h_2)\, g/fy \qquad (4)$$

where f = Coriolis parameter, y = total distance across stream, and h_1 and h_2 = average height of sea surface above datum.

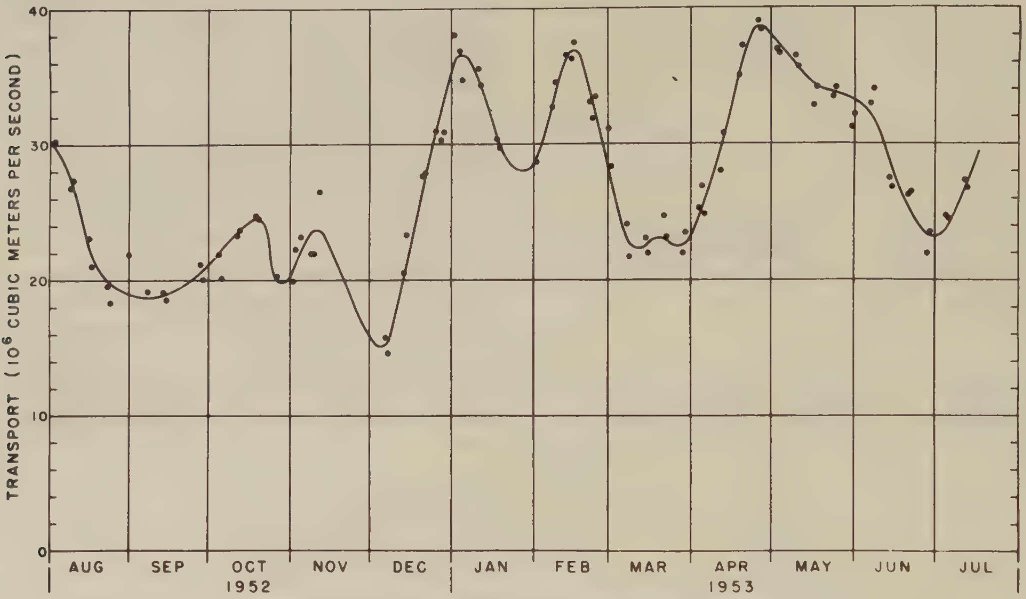

Fig. 2--Mass transport of the Florida Current

Figure 3a shows the transport for the year 1952-1953 as well as the difference between the Havana and Key West tide gages averaged over one-week intervals. Key West tide-gage data terminate in December, 1952, when this gage ceased operating. The qualitative agreement between the two curves is good, indicating that the surface current in the Straits of Florida is probably a good index of transport. Note that the rapid change in transport observed in December, 1952, is also observed on the tide-gage records and confirms the reality of the electrical observations. Corrections for atmospheric pressure and local wind effects have not been made.

Figure 3b shows a similar curve, comparing the electrically measured transport with changes in the slope of the sea surface between Bermuda and Charleston, which has been used as a measure of Gulf Stream transport. The agreement as to detail is poor, although there seems to be some general agreement on a large overall scale, leaving the way open for a number of possible explanations. It is possible that the surface current in the open ocean is determined more by local wind effects than by the overall motion of the water. In this case the average surface current (and hence the surface slope) no longer is a measure of transport. On the other hand, it is possible that the mass transport through the Bermuda-Charleston section is not proportional to the transport through the Key West-Havana section, the difference in transport being made up by the Antilles Current, or that the Charleston tide gage is affected by local piling up of water by the wind.

Correlation with the Atlantic wind system--According to a recent paper [MUNK, 1950], the transport of the Gulf Stream system is proportional to the curl of the wind stress over the Atlantic. Munk was able to obtain good agreement between the theoretical transport computed from the normal wind stress over the Atlantic and the known average value of transport. We now examine the correlation between monthly averages of wind and monthly averages of transport, and show there is no significant direct correlation over the interval for which data are available.

To obtain a measure of the wind stress curl over the Atlantic requires knowledge of the relation between wind stress and wind speed as well as information on the actual wind distribution. Neither of these can be accurately obtained. Moreover, even if the exact form of the wind-stress equation were known, it would not be possible to evaluate accurately the average wind stress from the average pressure maps unless the stress were a linear function of the speed. Instead of evaluating the average of the wind stress curl over a given area of the Atlantic, we may, as a suitable

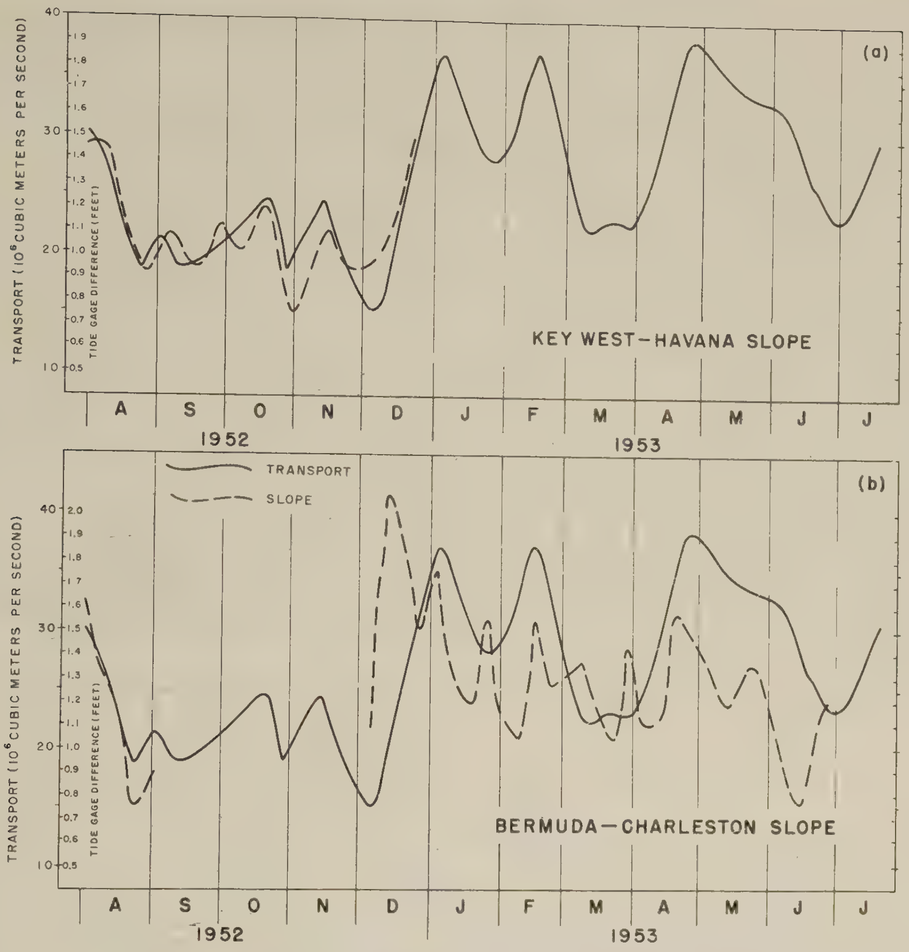

Fig. 3--Comparison of surface slope and transport (tide-gage differences are uncertain by an unknown additive amount)

equivalent use the circulation of the wind stress around a contour enclosing the same area. In view of the difficulty of obtaining the wind stress, we will investigate the use of the wind itself as the parameter for correlation.

The result of this analysis is shown in Figure 4. The units of the ordinates in these curves are arbitrary. The curve for trade-wind stress was obtained on the assumption that the drag coefficient is a constant and that the winds are relatively steady throughout the period over which the average was taken. The close resemblance which this curve bears to the other curves of trade-wind velocity and Atlantic wind circulation indicates that the choice of wind rather than wind stress for correlation with the transport is not a serious source of error, but will prevent the selection of one as the significant parameter.

Comparison of these curves with that of transport shown on the same figure indicates that there is no immediate good correlation between the variables in question. In order to obtain a quantitative measure of this preliminary conclusion, a correlogram was made for the wind circulation and transport for various months of phase shift between the two variables. The first positive correlation occurs with a -0.5-month phase lag, corresponding to a transport which leads the wind stress. It is assumed that this is a fortuitous correlation. Further positive correlations of the order of 0.5 are found at 6.5- and 18-month phase lag. It is apparent that no positive statement can be made about the relation between monthly average wind and transport on the basis of correlogram analysis, and it is quite possible that additional data will tend to lower the correlations obtained.

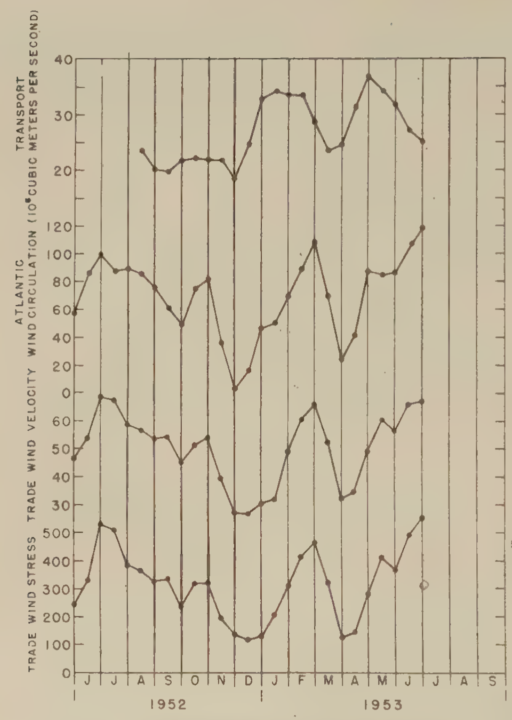

Fig. 4--Comparison of transport and the Atlantic wind system

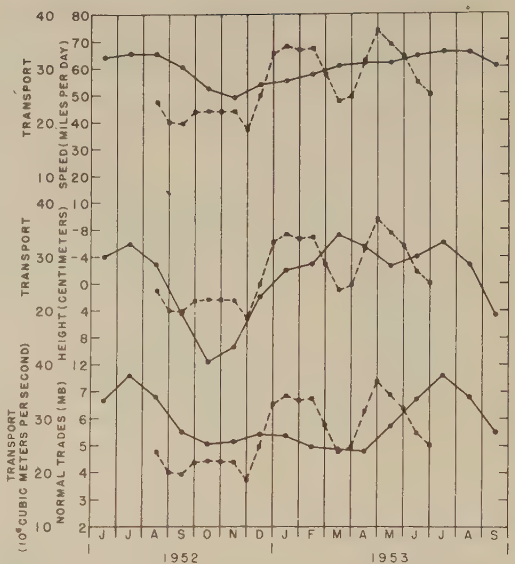

Fig. 5--Comparison of transport and normal curves of surface current, the Miami tide gage, and Atlantic wind circulation

There are, however, a number of serious objections to the analysis as here undertaken. Mathematically we cannot assume that the steady-state solution due to Munk will in any sense be applicable to the more rapidly changing regime here encountered. The method employed to reduce the weather map to a single significant number is not necessarily a reliable and sensitive means of measuring the significant changes in the wind circulation under all possible conditions. Further, it is intuitively clear that simultaneous changes in the wind strength along various portions of the contour will not produce a corresponding change in transport at the same time in the Straits of Florida. Phases should be introduced, but this can be accomplished only on the basis of some mathematical model which will suggest the required magnitudes. Moreover, the nearer segments may be more important. Finally, it must be pointed out that even on the basis of the most elementary mathematical model one cannot expect simple correlation between driving force and velocity (stress and transport).

As a test of the theory that the segments close to the Straits of Florida exert a dominant influence on the more rapid variations encountered within the seasonal curve, a comparison was made of the geostrophic wind off the coast of Florida and the southeastern Unites States with transport. The correlation obtained indicates that the flow through the straits may be predominantly controlled by the winds in this region; however, the data available are not sufficient to make a positive statement as to the significance of this result. In particular, it was noted that the rapid increase in transport observed in late December, 1952, does correspond to a complete reversal of the wind in the same period. The wind opposed the flow before, and aided the flow after, January 1, 1953. Reasonable correlation exists beyond that point.

Comparison with normal curves--Previous analyses of the factors contributing to the variations in the transport of the Gulf Stream have been carried out on the basis of 'normal' curves in the sense of month-by-month averages taken over many years. Figure 5 shows the normal curves of surface current in the Florida Straits [FUGLISTER, 1951], the height of the Miami tide gage, and the Atlantic wind circulation [CHASE, 1954]. On each there has been superposed the curve of monthly average transports (dotted). It has been considered significant in the past that the various normal curves show considerable similarity in shape. The 1952-1953 curve of transport which has been superposed shows large, relatively short-period variations about the normal curves while following their general trend. This is particularly noticeable in the case of the surface current which by previous argument appears to be a good index of transport. From the fact that these short-term variations do not appear in the normal curves, it may be deduced that they are not regular annual phenomena but probably depend on essentially random effects, meteorological and otherwise.

Variations of tidal period

The relation between the lunar transit and variations in the transport was noted by PILLSBURY [1890]. The effect is thought to be produced in the following way.

Consider the Straits of Florida as a channel and the Atlantic and Gulf as two large reservoirs. The tide in the Atlantic (Miami) is semi-diurnal, the diurnal components being only ten per cent of the amplitude of the semi-diurnal ones. The tide in the Gulf is mainly diurnal, but there are times when the amplitude is greatly reduced and the appearance of the tidal record is essentially semi-diurnal.

The effect of the tidal oscillations in the Atlantic will be to send a long wave up the Florida Straits in a direction opposite to the flow of the Florida Current. This view is justified by the tidal differences tabulated for the various well-exposed points along the Florida Keys. High water arrives progressively later as one goes down the Keys toward Key West, the total difference between Miami and Key West being about two hours. This corresponds well to the time of propagation of a long tidal wave, computed from $\sqrt{gd}$, with $d = 650$ m. Such a wave, which is much longer than the depth of the channel in which it propagates, has maximum transport at maximum tidal height; that is, we expect a minimum in the transport at Key West two hours after high water at Miami. This simple expectation is not realized since it neglects the effect of the Gulf tide. However, to further substantiate the theory of the progressive tidal wave, we will compute the transport of such a wave at a time when the amplitude of the Gulf tide is at a minimum. This occurred on August 22, 1952, during the period when continuous data were obtained. Examination of the record shows a tidal transport amplitude of approximately 4×10^6 m^3/sec. On the other hand, the amplitude of the transport of a long wave is given by

$$T = Agh/v \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Inserting the values for the Florida Straits

$A = 1.6 \times 10^8$ m^2 - Area of section
$h = 0.22$ m - Tidal amplitude
$v = 82$ m/sec - Velocity of tidal wave

we obtain approximately 4×10^6 m^3/sec, in good agreement with the measured amplitude.

Harmonic analysis--To obtain the harmonic components of tidal frequency found in the transport curve, Fourier analyses were made of various groups of 24-hr data, using midnight to midnight as the standard interval and employing a 24-ordinate scheme for the numerical analysis. The analysis was carried out to obtain the 24-, 12-, and 8-hr components using one-hour averages of transport as ordinates. The attenuating effect of such an averaging process on the amplitudes is only 0.05 pct. These components were subsequently separated into 12-, 12.4-, 24-, and 25.8-hr components by the use of a harmonic dial technique.

Table 1--Numerical results of harmonic analysis of transport data

Tidal component	Tidal period	Average amplitude of transport coefficient	Amplitude of tidal coefficient[a]			Coefficient of tide-producing force
			Miami	Key West	Galveston	
	hr	10^6 m^3/sec	ft	ft	ft	
M_2	12.42	3.8	1.20±0.37	0.56±0.11	0.31±0.08	0.45 ± 0.09
S_2	12.00	1.6	0.24±0.06	0.17±0.04	0.10±0.01	0.21 ± 0.06
K_1	23.93	3.6	0.13±0.04	0.29±0.09	0.38±0.10	0.27 ± 0.09
O_1	25.82	3.4	0.11	0.29	0.36	0.19

[a] The tolerances given for the tidal coefficients represent the effect of smaller coefficients of only slightly different period which could not be separated in the analysis of transport.

The results of the harmonic analysis are shown in Table 1, together with the coefficients of the tide-producing forces, and the tidal harmonics at Key West, Miami, and Galveston Bay. It should be noted that the harmonic components obtained by the analysis of transport are in a ratio which is between those of the semi-diurnal Atlantic tide (Miami) and the diurnal Gulf tide (Galveston), confirming the dependence of the transport on both tidal systems.

Comparison with tide data--A solution to the hydrodynamical problem of the Florida Straits-Atlantic-Gulf of Mexico system which is useful in interpreting currents in the Florida Straits has not been obtained. A complete solution must take into account Coriolis force, stratification of the water, and slope of the sea bottom. In order to test the idea that both Atlantic and Gulf tides play a significant role in the diurnal variation of the transport, we have combined the tidal harmonics of the Miami and Tampico tide stations with suitable phases so as to give the simultaneous effects at the Key West-Havana section. The result of this rather arbitrary procedure, together with a curve of transport for August, 1952, is shown in Figure 6. There has been no attempt to weight the two tidal components. The curve is simply a linear combination of existing tidal amplitudes. The Miami tide, representative of the Atlantic, is displaced by two hours and inverted to represent the time of travel of the long wave up the Florida channel. The Tampico tide is displaced by six hours for similar reasons.

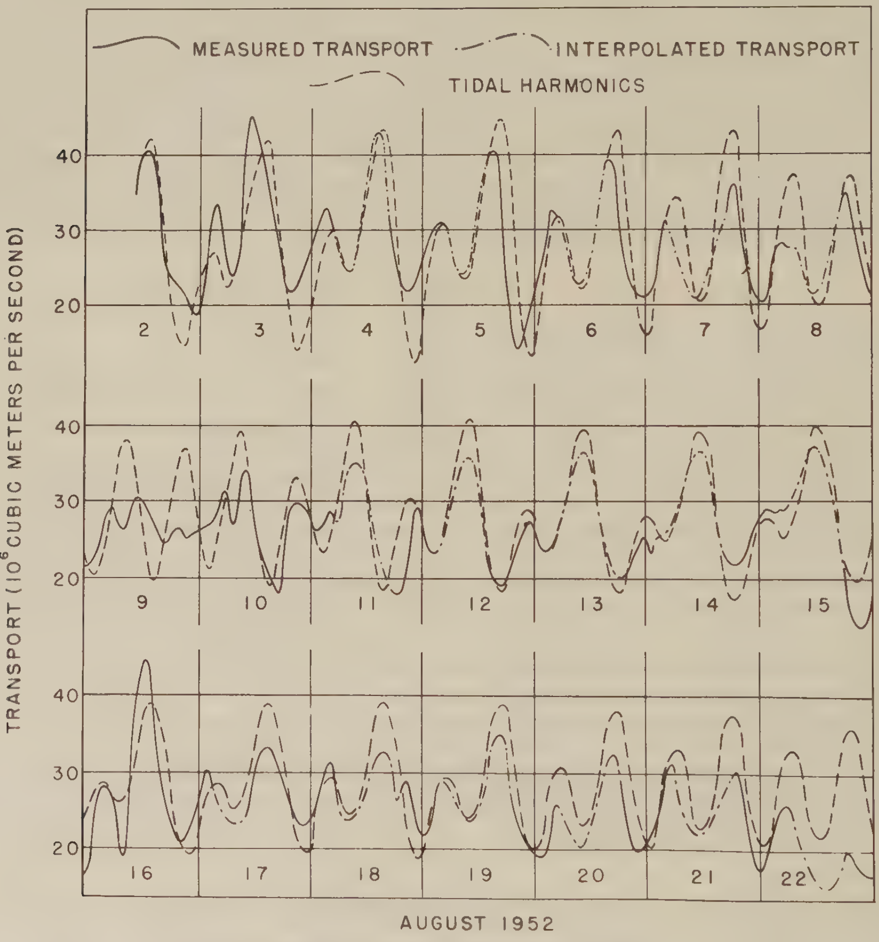

Fig. 6--Transport and combined tidal harmonics

The resulting agreement is good, except in those regions where the amplitudes of the tidal transport are small. Here other influences, such as local winds, may be significant. It is thought that this agreement may be taken to indicate that the above explanation of the tidal dependence of the transport is essentially correct in so far as it points out the two pertinent parameters. No further significance should be attached to the linear combination of tidal components of the two stations employed.

Irregular fluctuations and short-term noise

Geomagnetic noise--In addition to the components discussed above, the records also contain fluctuations of unpredictable amplitude and duration. The amplitude of these fluctuations is usually within a given range for as long as six hours but varies rapidly from day to day. These fluctuations are due to ionospheric or geomagnetic disturbances which produce Earth currents whose disturbing influence has long been recognized by the wire-communications engineer. The largest amplitude recorded during the year was approximately 1.5 v over a distance of 162 km, or ten mv/km. Potential gradients larger by a factor of 10^3 have been reported on long-line communication cables during severe geomagnetic disturbances in years of sunspot maxima.

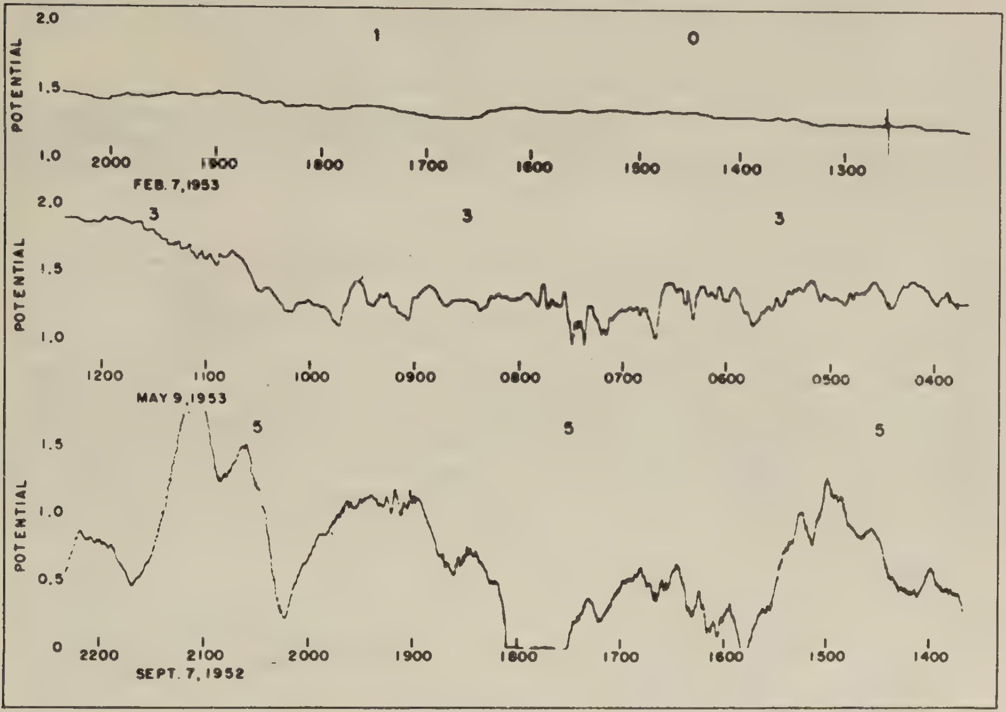

Fig. 7--The effect of geomagnetic disturbance on the electric potential

Figure 7 shows three sample records selected to show the range of geomagnetic effect encountered during the year. The numbers shown along the top edge of each record are the Cheltenham K indices, which are measures of the intensity of the disturbance of the geomagnetic field during consecutive three-hour periods. The correspondence between high K index and record noise was consistently observed throughout the year. The large majority of records obtained resembles the middle sample corresponding to a K index of 3. Long periods with index 0 are rare, and the one shown is the quietest record obtained.

Elementary electromagnetic theory indicates that the voltage measured in the loop consisting of the cable and the water above it may be related to the time rate of change of the component of the geomagnetic field normal to the plane of the loop. It should be noted that whereas the emf due to water motion is independent of the location of the cable, the geomagnetically induced emf depends on the vertical area of the cross section above the cable.

It follows directly from the law of induction that

$$E = - \mu A \, (\partial/\partial t) \, [H(t) \cos \Phi(t)] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where E is the induced emf, A the area of the section, H the average horizontal component of the field, and Φ the angle between the normal to the section and the direction of H. Examination of a magnetogram indicates that the required time derivative of the term $H \cos \Phi$ cannot be obtained accurately by numerical means. As an alternative, however, we may compare the integrated voltage with the magnetic field itself. Integrating (6) with respect to time yields

$$\int_0^t E\,dt = \mu A\,[H(o)\cos\Phi(o) - H(t)\cos\Phi(t)] \qquad (7)$$

This expression may now be expanded in terms of the time average values of H and Φ, $\overline{H}$ and $\overline{\Phi}$, and their time dependent perturbations h (t) and ϕ (t) to obtain

$$\int_0^t E\,dt = \mu A\,[H(o)\cos\Phi(o) - \overline{H}\cos\overline{\Phi}\cos\phi(t) + h(t)\sin\overline{\Phi}\sin\phi(t) - h(t)\cos\overline{\Phi}\cos\phi(t) + \overline{H}\sin\overline{\Phi}\sin\phi(t)] \qquad (8)$$

The first term depends only on the lower limit of the integration and is constant in time; the second term is essentially constant in time since ϕ (t) is small; the third term is negligible since it involves the product of two small factors. This leaves the last two terms as the major time-variant contributions. Recognizing that cos ϕ (t) $\approx$ 1, we obtain

$$\int_0^t E\,dt = \mu A\,[\text{const} - h(t)\cos\overline{\Phi} + \overline{H}\sin\overline{\Phi}\sin\phi(t)] \qquad (9)$$

These terms express respectively the contributions of the fluctuations of H and D.

This equation will now be used to compare the noise with the fluctuations of the geomagnetic field as recorded by the closest magnetic observatory in San Juan, Puerto Rico. We have selected the magnetograms for September 7 and 28, 1952, for the comparison because these days were magnetically active. The required integration was performed numerically by 20-min intervals after subtraction of the average value and the principal tidal component of transport. The result of this integration together with the evaluation of the right-hand side of (9) are given in Figure 8. It should be noted that the agreement with respect to fine detail is limited by the 20-min interval chosen for

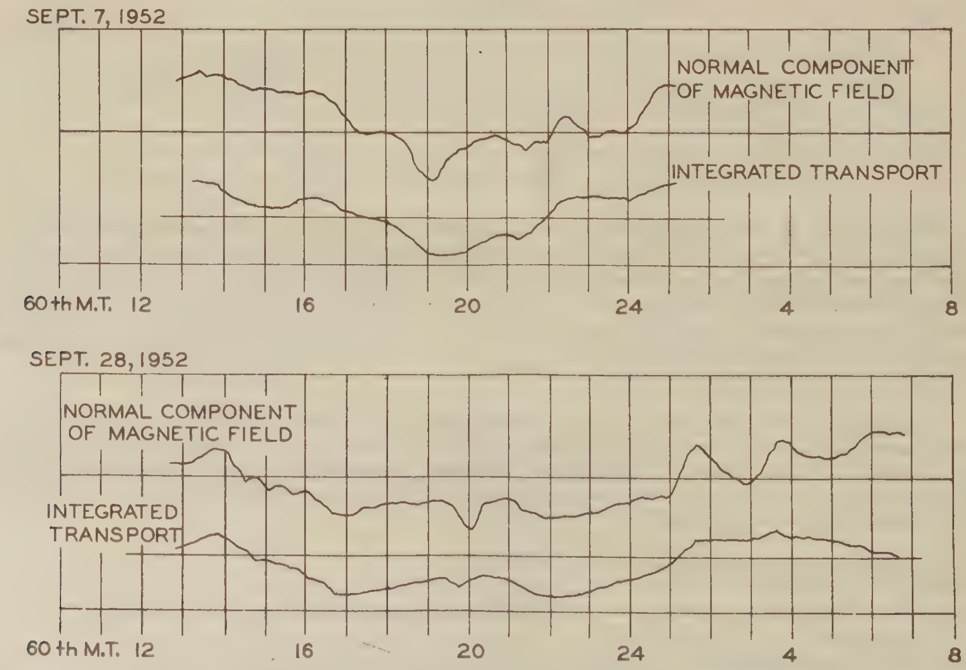

Fig. 8--Comparison of integrated transport with geomagnetic field the integration and by the physical separation of the cable site and the magnetic observatory. However, the agreement demonstrated does indicate that the noise observed on days having a high Cheltenham K index may be ascribed to the variations in the magnitude and direction of the horizontal component of the field. (Note that the transport is measured in terms of the vertical component of the field whose fluctuations produce only a second-order effect.)

Atmospheric noise--It was also noted that electrical disturbances in the atmosphere, lightning, and so forth, will affect the record. The usual appearance of the record during times of electrical storms is characterized by short vertical lines apparently due to single electrical discharges. Since the duration of these pulses is short, it is not possible to obtain an estimate of the magnitude of the voltages involved.

Instrumentation

The essential details of the instrumental setup are shown in Figure 9. The apparatus consists of two electrodes placed in the sea, one on each edge of the stream connected through an overload cut-off and an attenuating pad to a recording potentiometer.

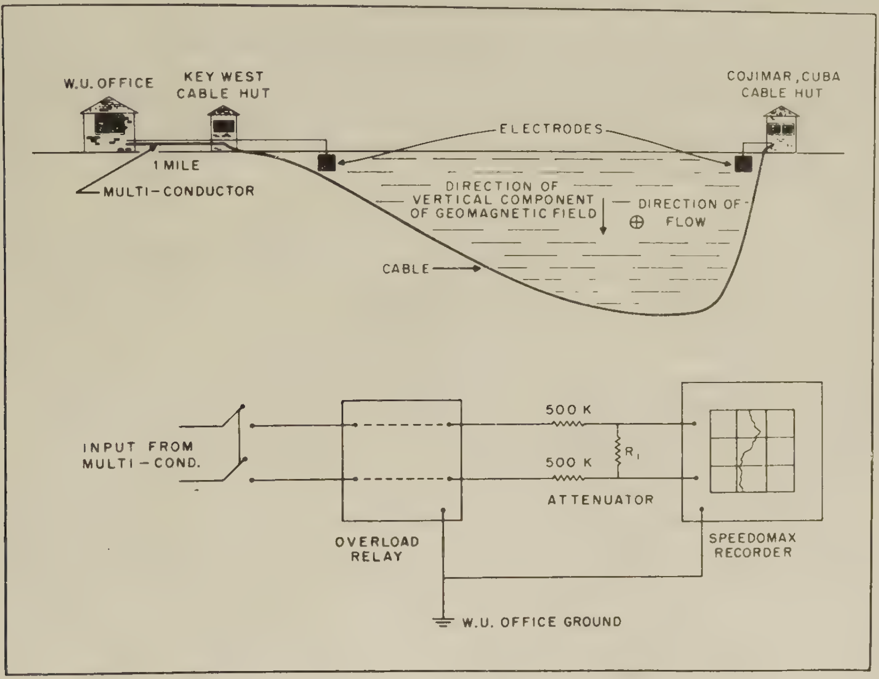
W.U. OFFICE
KEY WEST CABLE HUT
COJIMAR, CUBA CABLE HUT
ELECTRODES
1 MILE
MULTI-CONDUCTOR
DIRECTION OF VERTICAL COMPONENT OF GEOMAGNETIC FIELD
DIRECTION OF FLOW
CABLE
500 K
500 K
R₁
INPUT FROM MULTI-COND.
ATTENUATOR
OVERLOAD RELAY
SPEEDOMAX RECORDER
W.U. OFFICE GROUND

Fig. 9--Recording setup

The electrodes consist of 18 sets of specially matched GEK electrodes [VON ARX, 1950] connected to the recording equipment by the Western Union no. 2 cable whose parameters are

Copper resistance	990 ohms
Dielectric resistance	2.06 megohms

The effective load impedance at Key West is one megohm while the average recorded voltage is approximately one volt. Using these values and the cable parameters, it may be shown that no correction need be made for cable losses, the error being less than 0.1 pct which is less than the errors inherent in the recording and reading process.

During August, 1952, Key West-Havana data were obtained daily from 17h 00m until 06h 30m and on weekends from 17h 00m Friday until 06h 30m Monday, as well as on holidays. The daily recording program was abandoned at the end of August and only continuous weekend recording retained.

Conclusion

It has been shown that the cross-stream potential is a good measure of transport in the case of the Florida Straits. The major disturbing factor is the activity of the geomagnetic field which under most conditions prevents correlation of the instantaneous transport with the instantaneous voltage. Further uncertainty is introduced by the effects of bottom conductivity and the sloping sea bed. However, these effects are estimated to be small.

Summary--The geomagnetic disturbance has been successfully related to the horizontal component of the Earth's field. The validity of the surface slope as an index of transport in the Florida Straits has been confirmed. The tidal modulation of the transport has been shown to depend on both the Atlantic and Gulf tides. An analysis of the relation between the Atlantic wind system and the seasonal variation of the transport of the Gulf Stream has failed to yield positive results, and calls for a more sophisticated mathematical approach.

The program of measurements has been extended for one additional year with a view toward further investigation of the seasonal variation of the transport and other open questions.

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A METHOD FOR RENDERING WOOD RESISTANT TO MARINE BORERS.[1]

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ABSTRACT

The *in situ* precipitation of toxic materials in wood by double impregnation appears to have been inadequately tested as a borer-proofing method. A simple and economical method for borer-proofing wood by successive impregnations with copper sulfate and sodium hydroxide is described. This method has afforded complete protection to panels of pine and fir for more than two years. It appears to protect equally well against both shipworm and gribble.

INTRODUCTION

The replacement of wooden underwater structures damaged by marine borers is an expense faced by nearly every individual or group that maintains such structures. Damage from borers ranges from little or none in highly polluted waters to wide-spread practically complete destruction such as that which occurred in San Francisco Harbor in 1917-1921 (Atwood and Johnson 1924).

Most of the borer-proofing methods now in use involve the purchase of pre-treated lumber and timbers, or the expenditure of considerable sums for toxic paints or other surface-applied protective materials. The technique of borer-proofing by precipitation of borer-repellent chemicals *in situ* in the fibers of wood appears to have been largely overlooked. The only use of this technique seems to have been a successful double impregnation with copper sulfate and sodium carbonate tested by the Chemical Warfare Service (Atwood and Johnson 1924, pp. 207 and 214) which was borer-proof during the 161 days of test. Precipitation of toxin *in situ* in wood ensures penetration, avoids the search for specific solvents for toxins, avoids problems of adhesion failure, and should make available for testing almost every chemical compound which can be formed from the reaction of two solutions. The results presented in this paper are presented as an example of the economy and possible efficacy of the double impregnation method.

The double impregnation described here requires no specialized equipment, uses small quantities of inexpensive chemicals available at most drug stores, and uses methods available to everyone. It consists of precipitation of copper hydroxide in the fibers of the wood by soaking in copper sulfate and then in sodium hydroxide.[2] Wooden panels treated by this method have been afforded complete protection for more than two years in waters heavily infested with both gribbles and marine borers. This degree of protection appears to be comparable to the protection afforded by such related compounds as copper naphthenate, copper oleate, Cuprinol, etc.

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[1] Contribution No. 680 from Woods Hole Oceanographic Institution.

METHODS

The impregnations consisted of soaking the wood for 48 hours in a saturated aqueous solution of technical grade copper sulfate, followed by a quick water rinse, and by 48 hours' soaking in an aqueous solution of technical grade sodium hydroxide (¼ lb./gallon). Weights were employed to hold the wood submerged, and "sticks" to separate the boards and to hold them off the bottom of the bath. Both were shifted from time to time to enable the solutions to penetrate all the surfaces. At the end of the alkali impregnation the wood was rinsed repeatedly with water, and dried air-dry. After this it could be safely handled with the bare hands. Harmless white crystals of sodium sulfate usually appeared on the surface during drying.

Impregnation for 48 hours in each of the baths produced a dense layer of copper hydroxide 1/16 inch deep into the surface of the wood. Longer impregnation, of course, will produce deeper penetration. During immersion copper hydroxide appears to diffuse slowly inward into the wood, as well as outward to the sea water, for treated panels after immersion show a broad blue-stained band beneath the copper hydroxide layer (Figure 1).

Part of the panels were ¾″ x 6″ white pine, part were ⅝″ x 4″ fir, all were one foot long. The test pairs were hung from a horizontal brass chain 2-3 feet below lowest low water. The panels were assembled in pairs, each treated panel being paired with an untreated control panel which had been immediately adjacent to it in the original board. The suspending chain made a round turn about the brass bolt which held the pair together at their upper ends; the turn of chain served as a spacer between the panels. The lower ends of the panel pairs were bolted together in the same fashion as the upper ends. The treated panels were put at the head ends of the bolts so that they

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[2] A recent report (Baechler, 1953) describes a double impregnation method which uses copper sulfate and sodium chromate in the preservation of fence-posts.

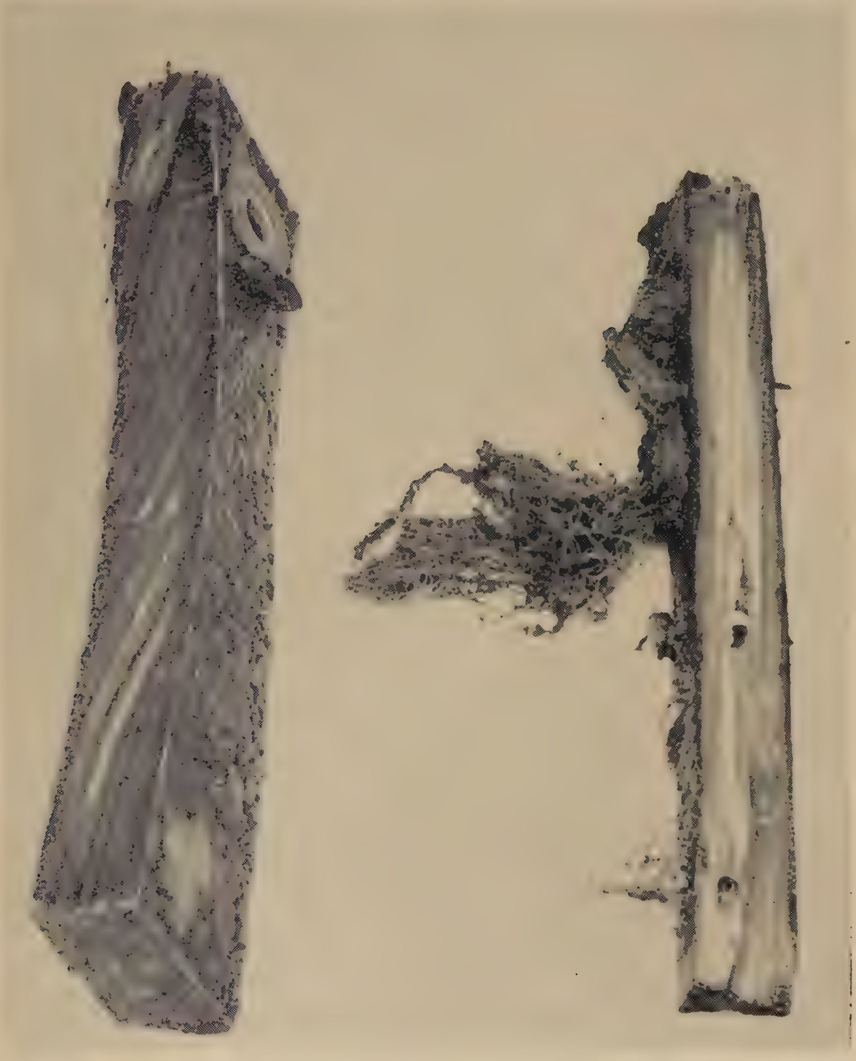

FIGURE 1. Treated panel (left) and untreated control panel (right) of pine after 13 months' exposure beneath the Woods Hole Oceanographic Institution dock, Great Harbor, Woods Hole, Mass. The layer of basic copper carbonate in and on the surface of the wood of the treated panel shows as a light band; the dark color of the inner wood of the treated panel is due to the copper hydroxide which appears to diffuse inward as well as outward during submergence.

could be identified at all times. The identifying number of each pair was stamped into the bolthead at the top of each pair.

RESULTS

The first set of test panels was suspended beneath the Woods Hole Oceanographic Institution's pier. Here it survived 1½ years before it was carried away during its second winter. One pair of panels was removed after 13 months' exposure. At that time the treated panel was moderately fouled but was free of borers, while the control was heavily fouled and contained two large borers (Figure 1). This test was not considered significant.

A second set of panels, 5 pairs in all, were hung from the Marine Biological Laboratory's floating dock in the Eel Pond at Woods Hole, Mass. Here they remained from 22 April 1949 until 8 September 1951. The waters of the Eel Pond are shallow, warm, and heavily infested with borers.

After 14 months in the Eel Pond the control panels were becoming narrow as borer and gribble (Limnoria) damage allowed their edges to erode away. They were honeycombed with borer and gribble tunnels and fairly heavily fouled with hydroids, while the treated panels were free from fouling and showed no visible damage of any kind.

By 8 September 1951 the control panels had disappeared except for small areas of badly riddled wood immediately around the washers and bolts. The conditions of the panels as removed from the water are shown in Figures 2 and 3. Each treated panel was split for internal inspection. Not a single borer was found in any of the treated panels, no gribble damage was present, nor (with one exception) were their surfaces more than very lightly fouled with hydroids and bryozoa (Figure 4).

DISCUSSION

At the termination of the test the treated panels were verdigris green in color and somewhat slippery to the hand. The green color was due to basic copper carbonate formed on and in the wood surface as copper ions leached slowly to the surface and came into contact with the oxygenated and carbonate-rich sea water. The basic copper carbonate is apparently either toxic or distasteful to gribbles and the larvae of borers.

The copper hydroxide precipated in the wood is only very slightly soluble and consequently can supply copper ions at a slow rate for a long period of time. After two years and four months of exposure the copper hydroxide layers in the treated panels were not visibly decreased in thickness nor appreciably dulled in color. They apparently contained reserves of copper adequate for still longer exposure.

Cost estimates

The 25 square feet of lumber used in the tests and preliminary trials were treated with 5 lbs. of copper sulfate (more than 4 pounds of which were recovered by allowing the sulfate bath to evaporate after the test panels were prepared), and 1 lb. of sodium hydroxide. The total cost of chemicals for the treatment was about $1.90. In practical application, the construction of two water-tight copper-fastened wooden troughs for the solutions would be a further, but usually not excessive, cost. The troughs need to be built only slighly longer, wider, and deeper than the wood to be treated.

Lumber or timbers to be treated by this method should be pre-cut to size so that the end-grain as well as the sides may be penetrated and protected. If the weights atop the lumber and the "sticks" beneath and among it in the soaking troughs are shifted occasionally both the sides and ends will be treated simultaneously and evenly, giving uniform protection.

The method is best applied to pre-cut lumber and timbers, though untreated wood exposed by carpentry can be treated by several successive swab applications of the sulfate followed by several swabbings with caustic.

This method offers little promise in the field of piling protection where pressure-impregnation with creosote is general practice. The toxicity imparted by this method appears to have definite long-term protection value, but it is in the surface of the wood and this makes it less suitable for structures subject to heavy battering by boats, ice, flotsam, etc., for small areas of untreated wood bared by battering would allow borers to penetrate the untreated interior wood. Structures subject to less severe battering may be protected by treated bumper strakes and corner-trim applied over treated timber.

Cautions

Copper sulfate is an effective skin poison and should not be left in contact with the skin for more than a few minutes.

Sodium hydroxide is a strong caustic and should be kept from contact with the skin, mouth and eyes. Loops of copper wire, rubber hose, rope, or other non-ferrous material should be used to remove wood from the caustic bath.

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3

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The copper salts in and on the wood greatly accelerate the corrosion of iron. Any structures fabricated of wood so treated must be brass or copper-fastened. Iron in contact with the treated wood will not only corrode with excessive rapidity, it will inactivate the copper and prevent its beneficial effects.

Caustics other than sodium hydroxide probably would work equally well. In the absence of sodium hydroxide, ordinary lye could be used. Ammonia will *not* substitute as the caustic, for it unites with copper to form a *soluble* complex hydroxide which will dissolve out of wood.

SUMMARY

Double impregnation affords a means of precipitating *in situ* in the fibers of wood any toxic material which can be formed by the reaction of two solutions. An efficient and economical example of borer-proofing by double impregnation is described.

The method consists of surface impregnation of the wood with copper sulfate, followed by a sodium hydroxide bath which precipitates copper hydroxide in the wood. Exposure to sea water produces a toxic layer of basic copper carbonate on and in the wood surface.

Woods panel treated by this method have been afforded complete protection from marine borers and from gribbles (Limnoria) for

FIGURE 2. Outer surfaces of the treated panels after two years and four months' exposure beneath the floating dock of the Marine Biological Laboratory, Eel Pond, Woods Hole, Mass. The panel at the left was fouled rather heavily with hydroids for reasons which are not known. The notch in the lower edge of the panel on the right is part of an auger hole which was present in the original board.

FIGURE 3. Inner surfaces of the treated panels after two years and four months' exposure in the Eel Pond, Woods Hole, Mass. The borer-riddled remains of the untreated control panels may be seen atop each panel. A few tube worms and barnacles occurred on these inner surfaces of the treated panels.

FIGURE 4. The treated panels, arranged in the same order as in Figure 3, after being split through the lower bolt-holes and turned to expose the split edges. A few strands of hydroid lie across the split edges of the panel on the left. The lower bolt-hole shows in the lower end of one or both parts of each panel. The lower central portion of the panel on the right shows a nail-hole which was present at the time the panel was prepared. No borers were present in any of the treated panels. The lower bolt from each panel pair, with its fragment of the lower end of the control panel has been laid out beneath each treated panel. The condition of the upper fragment of the control panel shows well at the left of the upper end of the panel on the right.

more than two years, while untreated panels of identical wood were completely destroyed.

The cost of chemicals, treatment troughs, etc., is less than the cost of commercial antifouling paint.

The chemicals required are available at most drug stores.

The copper sulfate and sodium hydroxide may be of the crudest technical grade.

The chemicals used are poisonous and must not be allowed to remain in contact with the skin, nor should they be allowed to enter the mouth or eyes. Treated wood after being washed and dried can be safely handled.

The treated wood requires brass or copper fastenings. Iron in contact with it destroys the protective value of the copper salts and is very rapidly corroded away.

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Contribution No. 683

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THE BACTERICIDAL EFFECTS OF SUNLIGHT IN RELATION TO "LIGHT" AND "DARK" BOTTLE PHOTOSYNTHESIS EXPERIMENTS

EXTRAIT DU JOURNAL DU CONSEIL INTERNATIONAL
POUR L'EXPLORATION DE LA MER
VOL. XX. No. 1. 1954

The Bactericidal Effects of Sunlight in Relation to "Light" and "Dark" Bottle Photosynthesis Experiments.[1])

By

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THE Gran oxygen method for measuring photosynthesis (Gaarder and Gran, 1927) presupposes that respiration by native plankton populations is equal in both "light" (transparent) and "dark" (opaque) bottles. Steemann Nielsen (1952) has proposed that this precept is violated when observations are extended beyond 24 hours. He emphasizes that prolonged exposure to ultraviolet and visible solar radiations inhibits bacterial development in the light bottles. As a result the greater amount of respiration resulting from the dark condition is not a true indication of respiration in the light bottles. Estimates of photosynthesis on this basis would therefore be excessively high. Ryther and Vaccaro (1954) on the other hand obtained photosynthesis values from long-term oxygen experiments equal to or lower than those derived from experiments of 24 hours or less. The status of future measurements of photosynthesis by the oxygen method is dependent upon a resolution of these inconsistencies.

In support of his argument, Steemann Nielsen has cited the observations by Meader (1926), who demonstrated a measurable bactericidal effect from solar wave-lengths transmitted through a glass plate (8 mm. thick). However, Mashimo (1919) noted the effectiveness of a glass plate (10 mm. thick) in removing the bactericidal wave-lengths from sunlight. In neither of these two cases were the experimental conditions sufficiently related to the Gran oxygen technique to permit a realistic assessment of the problem.

The validity of Steemann Nielsen's contention is dependent upon positive demonstration that under the conditions of the experiment

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[1]) Contribution No. 683 from the Woods Hole Oceanographic Institution.

the effects of sunlight induce a measurable restriction on bacterial growth and respiration. As a result we have undertaken an investigation of the bactericidal effects of sunlight in light and dark bottle photosynthesis experiments. Our observations have failed to uphold Steemann Nielsen's viewpoint, in that no measurable bactericidal activity has been noted.

In general the literature supports three different opinions as to the effects of light energy on bacterial populations. Without notable exception all are in agreement that bacteria are sensitive to middle ultraviolet radiations (200—300 mμ). However, Ward (1892) and Mackie and Van der Lingen (1926) also attribute inhibitory activity to visible and infrared rays. A second viewpoint is upheld by Bayne-Jones and Van der Lingen (1923) and Coblentz (1924), who consider bacteria to be mildly sensitive to near ultraviolet radiations (300—390 mμ). Finally, what is probably the predominant opinion is typified by Bachem and Dushkin (1935), who restrict significant bactericidal activity to wave-lengths shorter than 300 mμ with a maximum activity corresponding to 265 mμ.

Besides wave-length, intensity and duration of exposure must be considered. The Bunsen-Roscoe law as supported by Bachem predicts that for unchanging cell sensitivity, equal products of intensity and time induce comparable bactericidal activity. Bachem holds that the lethal effects of ultraviolet radiations follow this mode of behaviour.

Ultraviolet solar radiation as modified by the earth's atmosphere is a case in point. At sea level the lower limit of the solar spectrum is in the vicinity of 290 mμ. As compared with middle ultraviolet these wave-lengths are not especially lethal for bacteria. However, the great intensity of solar radiation makes it an extremely effective bactericidal agent under ideal atmospheric and experimental conditions.

According to Luckiesh (1922) ordinary glass is opaque beyond the near region and generally opaque to energy wave-lengths shorter than 340 mμ. Steemann Nielsen is not unaware that glass possesses selective absorption characteristics for ultraviolet radiant energy but, as stated above, his interpretation is based on the Meader observation. In contrast to Meader's glass plate, the standard dissolved-oxygen bottle of the type commonly used in light and dark bottle experiments has an average wall-thickness of approximately 2·5 mm. We have studied the absorption spectrum for this glass using a constant source of ultraviolet radiations from a hydrogen lamp in a Beckman Model DU Quartz Spectrophotometer.

Figure 1 presents the percentage transmission as measured for wave-lengths between 280 and 350 mμ. At 350 mμ a little more than 50 % transmission was measured. Below 350 mμ the percentage removal increased rapidly until the glass proved opaque to more than 99 % of the incident intensity for wave-lengths shorter than 305 mμ. These results confirm those of Luckiesh in that all middle ultraviolet and more than 50 % of the near-ultraviolet wave-lengths were absorbed.

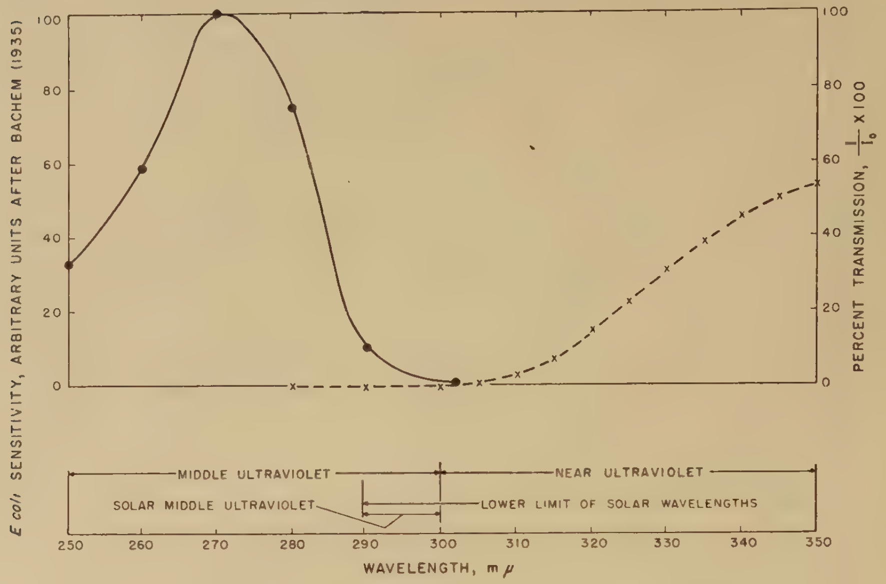

Figure 1. The spectral transmission through 2·5 mm. of glass (crossed) and the sensitivity of *Escherichia coli* (closed circles) for radiation 250—350 mμ.

For comparison the transmission-wave-length curve is related to the spectral sensitivity for *Escherichia coli* as determined by Bachem. The maximum *E. coli* sensitivity occurred at 270 mμ with only slight relative activity above 290 mμ and within the range of transmitted ultraviolet radiations.

Coblentz (1949) has defined the range of biologically effective solar radiation as extending from 290—315 mμ. The mean coefficient of absorption (α) for this range is represented by the relation

$$I = I_0 10^{-\alpha x},$$

where I_0 is the initial light-intensity and I the intensity through distance x. From Figure 1 the mean coefficient of absorption by the glass oxygen-bottle for wave-lengths 290—315 mμ is 7·4 per cm. or 1·85 per 0·25 cm., the average wall-thickness of the oxygen bottle.

The mean coefficient of sea water for wave-lengths 280—313 mμ as obtained from Hulburt (1928) is 0·010 per cm. of depth. Under typical conditions light and dark photosynthesis bottles are immersed under 10 cm. of sea water. Thus for 10 cm. of sea water the absorption coefficient approximates 0·25.

Combining the above analyses indicates that the total absorption coefficient for 10 cm. of sea water and the glass bottles is 2·10. From the foregoing equation the intensity of the biologically effective ultraviolet within the bottle is calculated as 0·8 $^0/_0$ of the intensity incident to the sea-water surface.

ZoBell and McEwen (1935) exposed shallow layers of filtered sea water in glass vessels to direct midsummer sunlight at La Jolla, California. The experiment was conducted so that the maximum effect of sunlight at this latitude could be observed. At a depth of 2 mm., two hours were required to effect a population reduction of approximately 50 %.

If the time-energy relationship of the Bunsen-Roscoe law holds, the time required for a comparable reduction of bacteria in the typical light and dark bottle experiment would amount to 250 hours with a zenith sun over calm, clear sea-water. Actually ZoBell and McEwen's data do not conform to the Bunsen-Roscoe law in that the bactericidal action of sunlight was limited to the first few minutes of exposure. On this basis the chance of detecting any significant bactericidal action in light and dark bottle experiments would be negligible.

Two experiments were designed to compare growth and oxygen consumption for sea-water suspensions of bacteria in light and dark bottles.

Experiment I.

Vineyard Sound sea water was collected at a site two miles from the nearest shore. The sample was quickly transported to the laboratory and passed through a millipore filter to remove plankton and particulate matter. The filtrate was seeded with a mixed population of bacteria obtained from a 24-hour plate culture of Vineyard Sound water. The initial bacterial count and dissolved-oxygen content were determined and the sample was siphoned into a series of light and dark 250 ml. standard dissolved-oxygen bottles. The bottles were filled to capacity so that the ground-glass stoppers made an air-tight seal with the sea water.

Half of the light and dark bottles were exposed to sunlight in the bottom of a tray suspended 10 inches below the surface of the water from a floating dock at Woods Hole. The bottles were laid parallel to the bottom and precautions were taken to avoid shadow interference.

The remaining light and dark bottles were illuminated with fluorescent lights in a white-painted tray cooled by a continuous flow of tap water. The distance of the submerged bottles to the light source was about 12 inches and the incident light intensity measured 1000 ft.-candles. The temperature of the tap water was 20 ± 2°C.

The experiment was conducted in July when the daily duration of sunlight approached 15 hours. Some precipitation occurred during the first 24 hours; otherwise clear weather prevailed. The period of exposure on the dock started about 10 a.m. and photometer measurements were taken by pointing a photo-electric cell, held over the tray, directly at the zenith. The maximum sunlight intensities were generally encountered about midday and amounted to 5,000 to 8,000 foot-candles while the minimum midday readings during cloudy conditions were about 1,000 foot-candles. The recorded temperature of the sea water was 22 ± 2°C.

Periodically a pair of light and dark bottles was removed from each tray and analysed for total bacterial count by the plating method and for dissolved-oxygen content by the Winkler method. The bacterial sample (1 ml.) was always removed first but only after releasing cells adhering to the inner walls of the bottle by scrubbing with a rubber policeman, care being taken to avoid the introduction of oxygen in the form of air bubbles.

Nutrient sea-water agar of the following composition was the media of choice:—

Aged sea water	1000 ml.
Bacto-peptone	5 gram.
Glucose	1 gram.
K_2HPO_4	·05 gram.
Bacto-agar	15 gram.

Appropriate dilutions were made so that the plates selected for counting after 5 days incubation at room temperature contained 30—300 colonies.

Table 1.

Average bacterial counts and dissolved-oxygen content of millipore-filtered sea water inoculated with marine bacteria and exposed to sunlight and artificial light in light and dark bottles.

	Sunlight				Artificial Light			
	Light Bottles		Dark Bottles		Light Bottles		Dark Bottles	
Time, hrs.	Cells per ml.	D. O. ml./l.	Cells per ml.	D. O. ml./l.	Cells per ml.	D. O. ml./l.	Cells per ml.	D. O. ml./l.
0	$2{\cdot}1\times10^{3}$	4·12	$2{\cdot}1\times10^{3}$	4·12	$2{\cdot}1\times10^{3}$	4·12	$2{\cdot}1\times10^{3}$	4·12
5	$1{\cdot}6\times10^{4}$	3·90	$4{\cdot}4\times10^{4}$	4·12	$4{\cdot}4\times10^{4}$	4·13	$3{\cdot}1\times10^{4}$	4·13
24	$2{\cdot}7\times10^{5}$	3·84	$2{\cdot}8\times10^{5}$		$2{\cdot}9\times10^{5}$	3·91	$5{\cdot}7\times10^{5}$	3·80
30	$3{\cdot}7\times10^{5}$	3·95	$7{\cdot}9\times10^{5}$	3·90	$5{\cdot}1\times10^{5}$	3·91	$5{\cdot}3\times10^{5}$	3·86
70	$1{\cdot}8\times10^{5}$	3·80	$1{\cdot}0\times10^{6}$	3·85	$6{\cdot}6\times10^{5}$	3·81	$1{\cdot}1\times10^{6}$	3·85
76	$2{\cdot}5\times10^{5}$	3·80	$3{\cdot}6\times10^{5}$	3·72	$4{\cdot}2\times10^{5}$	3·85	$7{\cdot}6\times10^{5}$	3·80

Table 1 relates the total bacterial counts to the dissolved-oxygen concentrations for this experiment. The absence of a phytoplankton population permitted the measurement of bacterial respiration in the absence of photosynthesis. It also obviated the possibility of obscure reactions between the two populations.

From an initial count of 2×10^3 cells/ml., the populations increased over the first 30 hours to about 5×10^5 cells per ml. Maximum populations were reached within 70 hours, at which time the numbers of bacteria in the dark bottles exceeded the total counts in the light bottles by almost an order of magnitude. However, at 76 hours the populations were essentially the same in all bottles.

The limit of sensitivity for the Winkler dissolved-oxygen method is approximately ± 0·05 ml./l. Thus a difference between any two samples of less than 0·10 ml./l. is not considered significant. The dissolved-oxygen concentration gradually decreased from 4·12 ml./l.

to about 3·80 ml./l. over a period of 76 hours. A comparison of the corresponding light and dark bottles reveals that with a single exception the light-bottle concentrations were never significantly higher than the related dark-bottle concentrations. The difference of 0·11 ml./l. between the light and dark bottles after 24 hours exposure under artificial light is inconsistent with the other observations and probably spurious.

Experiment II.

Sea water from Vineyard Sound was paper-filtered to remove the grosser particulate matter and dispensed into light and dark bottles, which were suspended off the Woods Hole dock. Here a study was made of the natural bacterial population in the presence of phytoplankton.

Table 2.

Average bacterial counts and dissolved-oxygen content of paper-filtered sea water in light and dark bottles as influenced by sunlight.

	Light Bottles		Dark Bottles	
Time, hrs.	Cells per ml.	D. O. ml./l.	Cells per ml.	D. O. ml./l.
0	$3{\cdot}1\times10^3$	4·50	$3{\cdot}1\times10^3$	4·50
7	$7{\cdot}9\times10^3$	4·55	$4{\cdot}5\times10^3$	4·45
24	$2{\cdot}8\times10^5$	4·36	$2{\cdot}2\times10^5$	4·31
31	$3{\cdot}2\times10^5$	4·64	$2{\cdot}7\times10^5$	
48	$3{\cdot}4\times10^5$	4·71	$4{\cdot}8\times10^5$	4·21
55	$1{\cdot}9\times10^5$	4·80	$3{\cdot}8\times10^5$	3·50
127	$1{\cdot}5\times10^5$	5·02	$1{\cdot}5\times10^5$	3·82
151	$6{\cdot}8\times10^4$	4·83	$1{\cdot}9\times10^4$	

Photosynthesis caused a gradual increase in the dissolved oxygen content of the light bottles indicating an excess of oxygen production over respiration. However, as shown in Table 2 the results are in agreement with Experiment I in that the growth of bacteria was essentially the same in the light and dark bottles.

Summary.

1. The majority of wave-lengths shorter than 350 mμ are effectively absorbed by glass bottles commonly used in this and other laboratories for dissolved-oxygen determinations.
2. Solar radiations transmitted by these bottles at a depth of 10 inches below the sea surface had no demonstrable lethal effects on suspensions of marine bacteria in sea water.
3. Bacteriological evidence is presented that the oxygen method of measuring photosynthesis is valid for experiments covering more than 24 hours.

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A METHOD FOR RENDERING WOOD RESISTANT TO MARINE BORERS.[1]

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ABSTRACT

The *in situ* precipitation of toxic materials in wood by double impregnation appears to have been inadequately tested as a borer-proofing method. A simple and economical method for borer-proofing wood by successive impregnations with copper sulfate and sodium hydroxide is described. This method has afforded complete protection to panels of pine and fir for more than two years. It appears to protect equally well against both shipworm and gribble.

INTRODUCTION

The replacement of wooden underwater structures damaged by marine borers is an expense faced by nearly every individual or group that maintains such structures. Damage from borers ranges from little or none in highly polluted waters to wide-spread practically complete destruction such as that which occurred in San Francisco Harbor in 1917-1921 (Atwood and Johnson 1924).

Most of the borer-proofing methods now in use involve the purchase of pre-treated lumber and timbers, or the expenditure of considerable sums for toxic paints or other surface-applied protective materials. The technique of borer-proofing by precipitation of borer-repellent chemicals *in situ* in the fibers of wood appears to have been largely overlooked. The only use of this technique seems to have been a successful double impregnation with copper sulfate and sodium carbonate tested by the Chemical Warfare Service (Atwood and Johnson 1924, pp. 207 and 214) which was borer-proof during the 161 days of test. Precipitation of toxin *in situ* in wood ensures penetration, avoids the search for specific solvents for toxins, avoids problems of adhesion failure, and should make available for testing almost every chemical compound which can be formed from the reaction of two solutions. The results presented in this paper are presented as an example of the economy and possible efficacy of the double impregnation method.

The double impregnation described here requires no specialized equipment, uses small quantities of inexpensive chemicals available

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[1] Contribution No. 680 from Woods Hole Oceanographic Institution.

at most drug stores, and uses methods available to everyone. It consists of precipitation of copper hydroxide in the fibers of the wood by soaking in copper sulfate and then in sodium hydroxide.[2] Wooden panels treated by this method have been afforded complete protection for more than two years in waters heavily infested with both gribbles and marine borers. This degree of protection appears to be comparable to the protection afforded by such related compounds as copper naphthenate, copper oleate, Cuprinol, etc.

METHODS

The impregnations consisted of soaking the wood for 48 hours in a saturated aqueous solution of technical grade copper sulfate, followed by a quick water rinse, and by 48 hours' soaking in an aqueous solution of technical grade sodium hydroxide (¼ lb./gallon). Weights were employed to hold the wood submerged, and "sticks" to separate the boards and to hold them off the bottom of the bath. Both were shifted from time to time to enable the solutions to penetrate all the surfaces. At the end of the alkali impregnation the wood was rinsed repeatedly with water, and dried air-dry. After this it could be safely handled with the bare hands. Harmless white crystals of sodium sulfate usually appeared on the surface during drying.

Impregnation for 48 hours in each of the baths produced a dense layer of copper hydroxide 1/16 inch deep into the surface of the wood. Longer impregnation, of course, will produce deeper penetration. During immersion copper hydroxide appears to diffuse slowly inward into the wood, as well as outward to the sea water, for treated panels after immersion show a broad blue-stained band beneath the copper hydroxide layer (Figure 1).

Part of the panels were ¾″ x 6″ white pine, part were ⅝″ x 4″ fir, all were one foot long. The test pairs were hung from a horizontal brass chain 2-3 feet below lowest low water. The panels were assembled in pairs, each treated panel being paired with an untreated control panel which had been immediately adjacent to it in the original board. The suspending chain made a round turn about the brass bolt which held the pair together at their upper ends; the turn of chain served as a spacer between the panels. The lower ends of the panel pairs were bolted together in the same fashion as the upper ends. The treated panels were put at the head ends of the bolts so that they

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[2] A recent report (Baechler, 1953) describes a double impregnation method which uses copper sulfate and sodium chromate in the preservation of fence-posts.

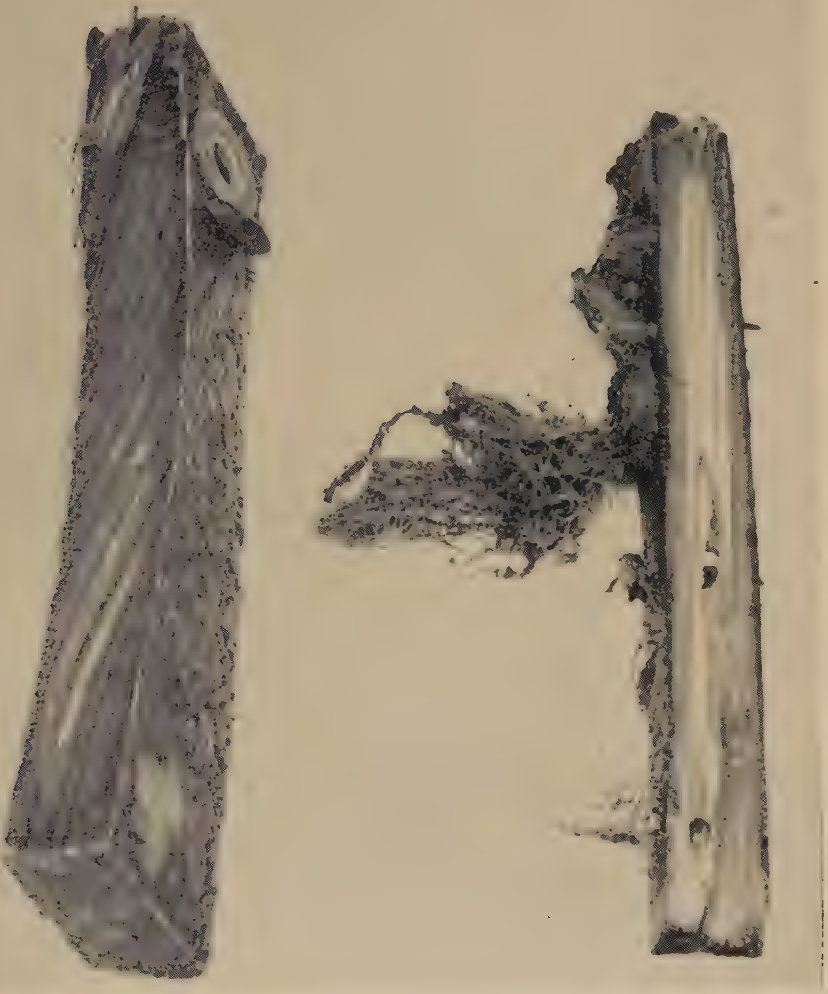

FIGURE 1. Treated panel (left) and untreated control panel (right) of pine after 13 months' exposure beneath the Woods Hole Oceanographic Institution dock, Great Harbor, Woods Hole, Mass. The layer of basic copper carbonate in and on the surface of the wood of the treated panel shows as a light band; the dark color of the inner wood of the treated panel is due to the copper hydroxide which appears to diffuse inward as well as outward during submergence.

could be identified at all times. The identifying number of each pair was stamped into the bolthead at the top of each pair.

RESULTS

The first set of test panels was suspended beneath the Woods Hole Oceanographic Institution's pier. Here it survived 1½ years before it was carried away during its second winter. One pair of panels was removed after 13 months' exposure. At that time the treated panel was moderately fouled but was free of borers, while the control was heavily fouled and contained two large borers (Figure 1). This test was not considered significant.

A second set of panels, 5 pairs in all, were hung from the Marine Biological Laboratory's floating dock in the Eel Pond at Woods Hole, Mass. Here they remained from 22 April 1949 until 8 September 1951. The waters of the Eel Pond are shallow, warm, and heavily infested with borers.

After 14 months in the Eel Pond the control panels were becoming narrow as borer and gribble (Limnoria) damage allowed their edges to erode away. They were honeycombed with borer and gribble tunnels and fairly heavily fouled with hydroids, while the treated panels were free from fouling and showed no visible damage of any kind.

By 8 September 1951 the control panels had disappeared except for small areas of badly riddled wood immediately around the washers and bolts. The conditions of the panels as removed from the water are shown in Figures 2 and 3. Each treated panel was split for internal inspection. Not a single borer was found in any of the treated panels, no gribble damage was present, nor (with one exception) were their surfaces more than very lightly fouled with hydroids and bryozoa (Figure 4).

DISCUSSION

At the termination of the test the treated panels were verdigris green in color and somewhat slippery to the hand. The green color was due to basic copper carbonate formed on and in the wood surface as copper ions leached slowly to the surface and came into contact with the oxygenated and carbonate-rich sea water. The basic copper carbonate is apparently either toxic or distasteful to gribbles and the larvae of borers.

The copper hydroxide precipated in the wood is only very slightly soluble and consequently can supply copper ions at a slow rate for a long period of time. After two years and four months of exposure the copper hydroxide layers in the treated panels were not visibly decreased in thickness nor appreciably dulled in color. They apparently contained reserves of copper adequate for still longer exposure.

Cost estimates

The 25 square feet of lumber used in the tests and preliminary trials were treated with 5 lbs. of copper sulfate (more than 4 pounds of which were recovered by allowing the sulfate bath to evaporate after the test panels were prepared), and 1 lb. of sodium hydroxide. The total cost of chemicals for the treatment was about $1.90. In practical application, the construction of two water-tight copper-fastened wooden troughs for the solutions would be a further, but usually not excessive, cost. The troughs need to be built only slighly longer, wider, and deeper than the wood to be treated.

Lumber or timbers to be treated by this method should be pre-cut to size so that the end-grain as well as the sides may be penetrated and protected. If the weights atop the lumber and the "sticks" beneath and among it in the soaking troughs are shifted occasionally both the sides and ends will be treated simultaneously and evenly, giving uniform protection.

The method is best applied to pre-cut lumber and timbers, though untreated wood exposed by carpentry can be treated by several successive swab applications of the sulfate followed by several swabbings with caustic.

This method offers little promise in the field of piling protection where pressure-impregnation with creosote is general practice. The toxicity imparted by this method appears to have definite long-term protection value, but it is in the surface of the wood and this makes it less suitable for structures subject to heavy battering by boats, ice, flotsam, etc., for small areas of untreated wood bared by battering would allow borers to penetrate the untreated interior wood. Structures subject to less severe battering may be protected by treated bumper strakes and corner-trim applied over treated timber.

Cautions

Copper sulfate is an effective skin poison and should not be left in contact with the skin for more than a few minutes.

Sodium hydroxide is a strong caustic and should be kept from contact with the skin, mouth and eyes. Loops of copper wire, rubber hose, rope, or other non-ferrous material should be used to remove wood from the caustic bath.

2

3

4

The copper salts in and on the wood greatly accelerate the corrosion of iron. Any structures fabricated of wood so treated must be brass or copper-fastened. Iron in contact with the treated wood will not only corrode with excessive rapidity, it will inactivate the copper and prevent its beneficial effects.

Caustics other than sodium hydroxide probably would work equally well. In the absence of sodium hydroxide, ordinary lye could be used. Ammonia will *not* substitute as the caustic, for it unites with copper to form a *soluble* complex hydroxide which will dissolve out of wood.

SUMMARY

Double impregnation affords a means of precipitating *in situ* in the fibers of wood any toxic material which can be formed by the reaction of two solutions. An efficient and economical example of borer-proofing by double impregnation is described.

The method consists of surface impregnation of the wood with copper sulfate, followed by a sodium hydroxide bath which precipitates copper hydroxide in the wood. Exposure to sea water produces a toxic layer of basic copper carbonate on and in the wood surface.

Woods panel treated by this method have been afforded complete protection from marine borers and from gribbles (Limnoria) for

FIGURE 2. Outer surfaces of the treated panels after two years and four months' exposure beneath the floating dock of the Marine Biological Laboratory, Eel Pond, Woods Hole, Mass. The panel at the left was fouled rather heavily with hydroids for reasons which are not known. The notch in the lower edge of the panel on the right is part of an auger hole which was present in the original board.

FIGURE 3. Inner surfaces of the treated panels after two years and four months' exposure in the Eel Pond, Woods Hole, Mass. The borer-riddled remains of the untreated control panels may be seen atop each panel. A few tube worms and barnacles occurred on these inner surfaces of the treated panels.

FIGURE 4. The treated panels, arranged in the same order as in Figure 3, after being split through the lower bolt-holes and turned to expose the split edges. A few strands of hydroid lie across the split edges of the panel on the left. The lower bolt-hole shows in the lower end of one or both parts of each panel. The lower central portion of the panel on the right shows a nail-hole which was present at the time the panel was prepared. No borers were present in any of the treated panels. The lower bolt from each panel pair, with its fragment of the lower end of the control panel has been laid out beneath each treated panel. The condition of the upper fragment of the control panel shows well at the left of the upper end of the panel on the right.

more than two years, while untreated panels of identical wood were completely destroyed.

The cost of chemicals, treatment troughs, etc., is less than the cost of commercial antifouling paint.

The chemicals required are available at most drug stores.

The copper sulfate and sodium hydroxide may be of the crudest technical grade.

The chemicals used are poisonous and must not be allowed to remain in contact with the skin, nor should they be allowed to enter the mouth or eyes. Treated wood after being washed and dried can be safely handled.

The treated wood requires brass or copper fastenings. Iron in contact with it destroys the protective value of the copper salts and is very rapidly corroded away.

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Contribution No. 683

R. F. VACCARO AND J. H. RYTHER

THE BACTERICIDAL EFFECTS OF SUNLIGHT IN RELATION TO "LIGHT" AND "DARK" BOTTLE PHOTOSYNTHESIS EXPERIMENTS

EXTRAIT DU JOURNAL DU CONSEIL INTERNATIONAL
POUR L'EXPLORATION DE LA MER
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The Bactericidal Effects of Sunlight in Relation to "Light" and "Dark" Bottle Photosynthesis Experiments.[1]

By

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THE Gran oxygen method for measuring photosynthesis (Gaarder and Gran, 1927) presupposes that respiration by native plankton populations is equal in both "light" (transparent) and "dark" (opaque) bottles. Steemann Nielsen (1952) has proposed that this precept is violated when observations are extended beyond 24 hours. He emphasizes that prolonged exposure to ultraviolet and visible solar radiations inhibits bacterial development in the light bottles. As a result the greater amount of respiration resulting from the dark condition is not a true indication of respiration in the light bottles. Estimates of photosynthesis on this basis would therefore be excessively high. Ryther and Vaccaro (1954) on the other hand obtained photosynthesis values from long-term oxygen experiments equal to or lower than those derived from experiments of 24 hours or less. The status of future measurements of photosynthesis by the oxygen method is dependent upon a resolution of these inconsistencies.

In support of his argument, Steemann Nielsen has cited the observations by Meader (1926), who demonstrated a measurable bactericidal effect from solar wave-lengths transmitted through a glass plate (8 mm. thick). However, Mashimo (1919) noted the effectiveness of a glass plate (10 mm. thick) in removing the bactericidal wavelengths from sunlight. In neither of these two cases were the experimental conditions sufficiently related to the Gran oxygen technique to permit a realistic assessment of the problem.

The validity of Steemann Nielsen's contention is dependent upon positive demonstration that under the conditions of the experiment

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[1] Contribution No. 683 from the Woods Hole Oceanographic Institution.

the effects of sunlight induce a measurable restriction on bacterial growth and respiration. As a result we have undertaken an investigation of the bactericidal effects of sunlight in light and dark bottle photosynthesis experiments. Our observations have failed to uphold Steemann Nielsen's viewpoint, in that no measurable bactericidal activity has been noted.

In general the literature supports three different opinions as to the effects of light energy on bacterial populations. Without notable exception all are in agreement that bacteria are sensitive to middle ultraviolet radiations (200—300 mμ). However, Ward (1892) and Mackie and Van der Lingen (1926) also attribute inhibitory activity to visible and infrared rays. A second viewpoint is upheld by Bayne-Jones and Van der Lingen (1923) and Coblentz (1924), who consider bacteria to be mildly sensitive to near ultraviolet radiations (300—390 mμ). Finally, what is probably the predominant opinion is typified by Bachem and Dushkin (1935), who restrict significant bactericidal activity to wave-lengths shorter than 300 mμ with a maximum activity corresponding to 265 mμ.

Besides wave-length, intensity and duration of exposure must be considered. The Bunsen-Roscoe law as supported by Bachem predicts that for unchanging cell sensitivity, equal products of intensity and time induce comparable bactericidal activity. Bachem holds that the lethal effects of ultraviolet radiations follow this mode of behaviour.

Ultraviolet solar radiation as modified by the earth's atmosphere is a case in point. At sea level the lower limit of the solar spectrum is in the vicinity of 290 mμ. As compared with middle ultraviolet these wave-lengths are not especially lethal for bacteria. However, the great intensity of solar radiation makes it an extremely effective bactericidal agent under ideal atmospheric and experimental conditions.

According to Luckiesh (1922) ordinary glass is opaque beyond the near region and generally opaque to energy wave-lengths shorter than 340 mμ. Steemann Nielsen is not unaware that glass possesses selective absorption characteristics for ultraviolet radiant energy but, as stated above, his interpretation is based on the Meader observation. In contrast to Meader's glass plate, the standard dissolved-oxygen bottle of the type commonly used in light and dark bottle experiments has an average wall-thickness of approximately 2·5 mm. We have studied the absorption spectrum for this glass using a constant source of ultraviolet radiations from a hydrogen lamp in a Beckman Model DU Quartz Spectrophotometer.

Figure 1 presents the percentage transmission as measured for wave-lengths between 280 and 350 mμ. At 350 mμ a little more than 50 % transmission was measured. Below 350 mμ the percentage removal increased rapidly until the glass proved opaque to more than 99 % of the incident intensity for wave-lengths shorter than 305 mμ. These results confirm those of Luckiesh in that all middle ultraviolet and more than 50 % of the near-ultraviolet wave-lengths were absorbed.

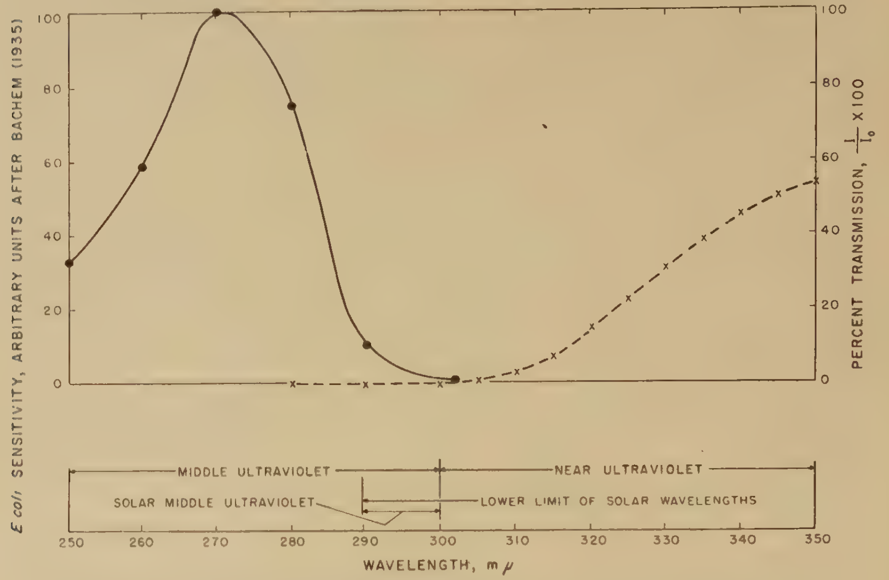

Figure 1. The spectral transmission through 2·5 mm. of glass (crossed) and the sensitivity of *Escherichia coli* (closed circles) for radiation 250—350 mμ.

For comparison the transmission-wave-length curve is related to the spectral sensitivity for *Escherichia coli* as determined by Bachem. The maximum *E. coli* sensitivity occurred at 270 mμ with only slight relative activity above 290 mμ and within the range of transmitted ultraviolet radiations.

Coblentz (1949) has defined the range of biologically effective solar radiation as extending from 290—315 mμ. The mean coefficient of absorption (α) for this range is represented by the relation

$$I = I_0 10^{-\alpha x},$$

where I_0 is the initial light-intensity and I the intensity through distance x. From Figure 1 the mean coefficient of absorption by the glass oxygen-bottle for wave-lengths 290—315 mμ is 7·4 per cm. or 1·85 per 0·25 cm., the average wall-thickness of the oxygen bottle.

The mean coefficient of sea water for wave-lengths 280—313 mμ as obtained from Hulburt (1928) is 0·010 per cm. of depth. Under typical conditions light and dark photosynthesis bottles are immersed under 10 cm. of sea water. Thus for 10 cm. of sea water the absorption coefficient approximates 0·25.

Combining the above analyses indicates that the total absorption coefficient for 10 cm. of sea water and the glass bottles is 2·10. From the foregoing equation the intensity of the biologically effective ultraviolet within the bottle is calculated as 0·8 $^0/_0$ of the intensity incident to the sea-water surface.

ZoBell and McEwen (1935) exposed shallow layers of filtered sea water in glass vessels to direct midsummer sunlight at La Jolla, California. The experiment was conducted so that the maximum effect of sunlight at this latitude could be observed. At a depth of 2 mm., two hours were required to effect a population reduction of approximately 50 %.

If the time-energy relationship of the Bunsen-Roscoe law holds, the time required for a comparable reduction of bacteria in the typical light and dark bottle experiment would amount to 250 hours with a zenith sun over calm, clear sea-water. Actually ZoBell and McEwen's data do not conform to the Bunsen-Roscoe law in that the bactericidal action of sunlight was limited to the first few minutes of exposure. On this basis the chance of detecting any significant bactericidal action in light and dark bottle experiments would be negligible.

Two experiments were designed to compare growth and oxygen consumption for sea-water suspensions of bacteria in light and dark bottles.

Experiment I.

Vineyard Sound sea water was collected at a site two miles from the nearest shore. The sample was quickly transported to the laboratory and passed through a millipore filter to remove plankton and particulate matter. The filtrate was seeded with a mixed population of bacteria obtained from a 24-hour plate culture of Vineyard Sound water. The initial bacterial count and dissolved-oxygen content were determined and the sample was siphoned into a series of light and dark 250 ml. standard dissolved-oxygen bottles. The bottles were filled to capacity so that the ground-glass stoppers made an air-tight seal with the sea water.

Half of the light and dark bottles were exposed to sunlight in the bottom of a tray suspended 10 inches below the surface of the water from a floating dock at Woods Hole. The bottles were laid parallel to the bottom and precautions were taken to avoid shadow interference.

The remaining light and dark bottles were illuminated with fluorescent lights in a white-painted tray cooled by a continuous flow of tap water. The distance of the submerged bottles to the light source was about 12 inches and the incident light intensity measured 1000 ft.-candles. The temperature of the tap water was 20 ± 2°C.

The experiment was conducted in July when the daily duration of sunlight approached 15 hours. Some precipitation occurred during the first 24 hours; otherwise clear weather prevailed. The period of exposure on the dock started about 10 a.m. and photometer measurements were taken by pointing a photo-electric cell, held over the tray, directly at the zenith. The maximum sunlight intensities were generally encountered about midday and amounted to 5,000 to 8,000 foot-candles while the minimum midday readings during cloudy conditions were about 1,000 foot-candles. The recorded temperature of the sea water was 22 ± 2°C.

Periodically a pair of light and dark bottles was removed from each tray and analysed for total bacterial count by the plating method and for dissolved-oxygen content by the Winkler method. The bacterial sample (1 ml.) was always removed first but only after releasing cells adhering to the inner walls of the bottle by scrubbing with a rubber policeman, care being taken to avoid the introduction of oxygen in the form of air bubbles.

Nutrient sea-water agar of the following composition was the media of choice:—

Aged sea water	1000 ml.
Bacto-peptone	5 gram.
Glucose	1 gram.
K_2HPO_4	·05 gram.
Bacto-agar	15 gram.

Appropriate dilutions were made so that the plates selected for counting after 5 days incubation at room temperature contained 30—300 colonies.

Table 1.

Average bacterial counts and dissolved-oxygen content of millipore-filtered sea water inoculated with marine bacteria and exposed to sunlight and artificial light in light and dark bottles.

	Sunlight				Artificial Light			
	Light Bottles		Dark Bottles		Light Bottles		Dark Bottles	
Time, hrs.	Cells per ml.	D. O. ml./l.	Cells per ml.	D. O. ml./l.	Cells per ml.	D. O. ml./l.	Cells per ml.	D. O. ml./l.
0	$2{\cdot}1\times10^{3}$	4·12	$2{\cdot}1\times10^{3}$	4·12	$2{\cdot}1\times10^{3}$	4·12	$2{\cdot}1\times10^{3}$	4·12
5	$1{\cdot}6\times10^{4}$	3·90	$4{\cdot}4\times10^{4}$	4·12	$4{\cdot}4\times10^{4}$	4·13	$3{\cdot}1\times10^{4}$	4·13
24	$2{\cdot}7\times10^{5}$	3·84	$2{\cdot}8\times10^{5}$		$2{\cdot}9\times10^{5}$	3·91	$5{\cdot}7\times10^{5}$	3·80
30	$3{\cdot}7\times10^{5}$	3·95	$7{\cdot}9\times10^{5}$	3·90	$5{\cdot}1\times10^{5}$	3·91	$5{\cdot}3\times10^{5}$	3·86
70	$1{\cdot}8\times10^{5}$	3·80	$1{\cdot}0\times10^{6}$	3·85	$6{\cdot}6\times10^{5}$	3·81	$1{\cdot}1\times10^{6}$	3·85
76	$2{\cdot}5\times10^{5}$	3·80	$3{\cdot}6\times10^{5}$	3·72	$4{\cdot}2\times10^{5}$	3·85	$7{\cdot}6\times10^{5}$	3·80

Table 1 relates the total bacterial counts to the dissolved-oxygen concentrations for this experiment. The absence of a phytoplankton population permitted the measurement of bacterial respiration in the absence of photosynthesis. It also obviated the possibility of obscure reactions between the two populations.

From an initial count of 2×10^{3} cells/ml., the populations increased over the first 30 hours to about 5×10^{5} cells per ml. Maximum populations were reached within 70 hours, at which time the numbers of bacteria in the dark bottles exceeded the total counts in the light bottles by almost an order of magnitude. However, at 76 hours the populations were essentially the same in all bottles.

The limit of sensitivity for the Winkler dissolved-oxygen method is approximately ± 0·05 ml./l. Thus a difference between any two samples of less than 0·10 ml./l. is not considered significant. The dissolved-oxygen concentration gradually decreased from 4·12 ml./l.

to about 3·80 ml./l. over a period of 76 hours. A comparison of the corresponding light and dark bottles reveals that with a single exception the light-bottle concentrations were never significantly higher than the related dark-bottle concentrations. The difference of 0·11 ml./l. between the light and dark bottles after 24 hours exposure under artificial light is inconsistent with the other observations and probably spurious.

Experiment II.

Sea water from Vineyard Sound was paper-filtered to remove the grosser particulate matter and dispensed into light and dark bottles, which were suspended off the Woods Hole dock. Here a study was made of the natural bacterial population in the presence of phytoplankton.

Table 2.

Average bacterial counts and dissolved-oxygen content of paper-filtered sea water in light and dark bottles as influenced by sunlight.

	Light Bottles		Dark Bottles	
Time, hrs.	Cells per ml.	D. O. ml./l.	Cells per ml.	D. O. ml./l.
0	$3{\cdot}1\times10^3$	4·50	$3{\cdot}1\times10^3$	4·50
7	$7{\cdot}9\times10^3$	4·55	$4{\cdot}5\times10^3$	4·45
24	$2{\cdot}8\times10^5$	4·36	$2{\cdot}2\times10^5$	4·31
31	$3{\cdot}2\times10^5$	4·64	$2{\cdot}7\times10^5$	
48	$3{\cdot}4\times10^5$	4·71	$4{\cdot}8\times10^5$	4·21
55	$1{\cdot}9\times10^5$	4·80	$3{\cdot}8\times10^5$	3·50
127	$1{\cdot}5\times10^5$	5·02	$1{\cdot}5\times10^5$	3·82
151	$6{\cdot}8\times10^4$	4·83	$1{\cdot}9\times10^4$	

Photosynthesis caused a gradual increase in the dissolved oxygen content of the light bottles indicating an excess of oxygen production over respiration. However, as shown in Table 2 the results are in agreement with Experiment I in that the growth of bacteria was essentially the same in the light and dark bottles.

Summary.

1. The majority of wave-lengths shorter than 350 mμ are effectively absorbed by glass bottles commonly used in this and other laboratories for dissolved-oxygen determinations.
2. Solar radiations transmitted by these bottles at a depth of 10 inches below the sea surface had no demonstrable lethal effects on suspensions of marine bacteria in sea water.
3. Bacteriological evidence is presented that the oxygen method of measuring photosynthesis is valid for experiments covering more than 24 hours.

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A/S L. IHRICH . COPENHAGUE

Contribution No. 684

J. H. RYTHER AND R. F. VACCARO

A COMPARISON OF THE OXYGEN AND ^{14}C METHODS OF MEASURING MARINE PHOTOSYNTHESIS

EXTRAIT DU JOURNAL DU CONSEIL INTERNATIONAL
POUR L'EXPLORATION DE LA MER
VOL. XX. No. 1. 1954

A Comparison of the Oxygen and ^{14}C Methods of Measuring Marine Photosynthesis.[1] [2]

By

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Introduction.

An experimental method of measuring photosynthetic rates of natural populations of phytoplankton was first described by Gaarder and Gran (1927). This method involves measuring the rate of oxygen production by the phytoplankton from the difference in the dissolved-oxygen content of sea-water samples enclosed in "light" (transparent) and "dark" (opaque) bottles. In the light bottle, the net effect of both photosynthesis and respiration is measured, while the dark bottle measures respiration alone. Assuming that respiration of the native flora and fauna is essentially the same in the light and dark bottles, the difference in their dissolved-oxygen concentrations after a given experimental period may be considered equal to the oxygen produced by photosynthesis.

Recently, a new technique for measuring photosynthesis was described by Steemann Nielsen (1951b, 1952). In this method, the rate of uptake of radio-active carbon by the phytoplankton is determined by adding small quantities of ^{14}C as carbonate to sea-water samples, removing the plankton after a given experimental period by filtration, and measuring its radio-activity. If the ratio of uptake of $^{14}C : ^{12}C$ is known, a direct measurement of carbon assimilation may thus be obtained.

The Gran oxygen method, or slight modifications thereof, has found rather widespread use among marine biologists. The most significant studies are perhaps those of Steemann Nielsen (1951a and references) in coastal waters off Denmark, and Riley (Riley

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[1] Contribution No. 684 from the Woods Hole Oceanographic Institution.

[2] This work was carried out with the assistance of a research grant from the National Science Foundation and under contract with the Office of Naval Research.

et al., 1949 and references) in the coastal and offshore waters of the north-western Atlantic.

The ^{14}C method was used by Steemann Nielsen to measure the production rate of organic matter in all of the major oceans of the world during the recent "Galathea" expedition. A comparison between some of his results from the "Galathea" cruise and Riley's earlier figures obtained with the oxygen method showed reasonably good agreement in coastal, eutrophic waters. However, Riley's values from the tropical Atlantic (i.e., Sargasso Sea) were considerably higher than those obtained by Steemann Nielsen for the tropical regions of the Indian Ocean (see Steemann Nielsen, 1952).

Although the reasons were not made clear why photosynthetic rates in two different oceans at two different times should agree, even to an order of magnitude, the discrepancy between the two sets of data led Steemann Nielsen to question the oxygen method as a technique for measuring photosynthesis in the open ocean. In defence of his data Riley (1953) has pointed out that the apparent discrepancy resulted largely from the respective choice of average photosynthesis values by the two workers, and that the actual range of values obtained in each case was very nearly the same.

This difference of opinion has cast doubt both upon earlier measurements of marine photosynthesis and upon the classical oxygen method as a tool for future studies. Steemann Nielsen's principal argument is based upon the contention that bacterial respiration in light and dark bottles is not equal, due to the bactericidal effects of sunlight. This hypothesis has been investigated by the present authors and is reported elsewhere (Vaccaro and Ryther, 1954). The need remains apparent, however, for a simultaneous comparison of the two methods. This report contains the results of some experiments in which such a comparison was made.

Methods.

Photosynthesis was measured by the oxygen and ^{14}C methods in cultures of the diatom, *Nitzschia closterium*, and in natural phytoplankton populations from Vineyard Sound.

Experiments were conducted in 250 ml. glass-stoppered bottles under artificial illumination provided by eight 40-W. fluorescent lamps, which produced an intensity of 1000 foot-candles incident to the bottles. The latter were completely immersed in circulating tap-water in a white-painted tray. The temperature of the cooling water ranged from 18° to 22°C.

Oxygen experiments.

Cultures of *Nitzschia* were centrifuged from their nutrient media and resuspended in filtered sea water collected from Vineyard Sound during June and July. Equal volumes of *Nitzschia* suspension containing varying cell concentrations were added to the experimental bottles, which were then carefully filled by siphon with filtered sea water.

In each experiment, three bottles were employed, the first used for an immediate determination of dissolved oxygen, the second placed in the water tray exposed to light, and the third wrapped in a black cloth bag, which was also completely immersed in the water bath. At the conclusion of the experimental period, the latter two bottles were removed and their dissolved-oxygen content measured. Differences between the oxygen concentrations of the light and dark bottles were considered to be equal to the oxygen produced by photosynthesis in the experiment. The glucose-carbon equivalent was obtained by multiplying the weight of the produced oxygen by 0·375.

The oxygen method, as described above, is subject to a basic source of error in that respiration of the phytoplankton in the light bottle is probably always somewhat higher than that in the dark bottle. This will obviously be so if there is any appreciable growth of the organisms in the light bottle. However, even if no cell division occurs, the conversion and metabolism of newly formed products of photosynthesis may result in a considerably higher respiration rate in the light bottle, particularly in the case of experiments lasting for several days. As a consequence of this "after effect of photosynthesis upon respiration", as it is described by Rabinowitch (1945), the estimate of respiration in the light bottle based upon that measured in the dark bottle is too low, resulting in correspondingly low values for photosynthesis.

^{14}C experiments.

^{14}C in the form of barium carbonate was converted to sodium carbonate and used in the synthesis of an artificial sea water in the same manner as described by Steemann Nielsen (1952), and the solution was sterilized by autoclaving. The activity of a diluted aliquot was then determined by re-precipitation as $Ba^{14}CO_3$ which was filtered and measured for activity corrected to zero thickness of sample, again following the method prescribed by Steemann Nielsen. Activity of the stock solution was $1{\cdot}39 \times 10^6$ cpm. per ml.

One ml. aliquots of the ^{14}C stock were added to the experimental bottles which were inoculated with *Nitzschia* and filled with filtered sea water, as in the light and dark bottle experiments. These were then placed in the water-bath exposed to the light.

At the conclusion of the experimental period the samples were filtered through a hydrosol millipore filter¹) capable of retaining all particulate matter above 0·5 μ in diameter. The filters were cut to size so that they could be mounted on a precipitation apparatus²) for filtration and on planchet holders for measurement of their activity. After the filtration, the filter was washed with 25 ml. of sea water and 10 ml. of 0·001 M HCl. The latter was found to be considerably faster than, and equally as efficient in removing traces of inorganic ^{14}C as, Steemann Nielsen's method of exposing the filters to fumes of

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¹) Lovell Chemical Co., Watertown, Mass.

²) E8-A precipitation apparatus: Tracer Lab. Inc., Boston, Massachusetts.

concentrated HCl. The filters were then mounted on planchet holders and dried for 24 hours or to constant activity in a desiccator containing silica gel. Their activity was measured with a Tracerlab SC-16 windowless flow-counter to an accuracy of ± 1 %.

The total CO_2 content of the sea water was determined from its temperature, pH, and salinity at the time it was dispensed into the experimental vessels from the equations of Buch, Harvey, Gripenberg, and Wattenberg (see Harvey, 1945). This was multiplied by the ratio of ^{14}C assimilated (activity of the filtered plankton) : ^{14}C available ($1{\cdot}39 \times 10^6$ cpm.), giving a first approximation of total CO_2-assimilation by the phytoplankton.

To obtain an accurate determination of photosynthesis from the above figure, the following sources of error, as discussed by Steemann Nielsen, must be corrected for:—

1. The isotope effect (i.e., the difference between the rate of uptake of ^{14}C and ^{12}C). On the basis of evidence presented by Steemann Nielsen and references cited by him, the ratio of ^{12}C : ^{14}C assimilation is taken as 1·06 : 1, thus requiring a correction of +6 % to be applied to the initial value.
2. The uptake of ^{14}C by processes other than photosynthesis. Uptake of ^{14}C in the dark by *Nitzschia* was found to equal approximately 1 % of that observed in the light in both 6- and 24-hour experiments and in different concentrations of *Nitzschia*. This is in good agreement with Steemann Nielsen's figures for *Scenedesmus*, and results in a correction factor of —1 %.
3. The loss of assimilated ^{14}C by respiration during the course of the experiment. This is a difficult figure to estimate, since it will vary not only with the length of the experimental period, but also with the rates of photosynthesis and respiration of the organisms. Steemann Nielsen has placed this at 4 % of total photosynthesis for a 4-hour experiment, although his basis for doing so is not clear. In view of the lack of evidence concerning this question and the difficulties involved in obtaining such measurements, no attempt will be made here to correct for this source of error.

A total correction of +5 % is therefore applied to the calculated CO_2-assimilation, as described above, and it is emphasized that this figure will fall below the true value for CO_2-assimilation by the uncorrected loss of respired ^{14}C.

Sensitivity of the oxygen and ^{14}C methods.

Duplicate samples analysed for dissolved oxygen by the Winkler method gave values which were generally reproducible to ±0·05 ml. O_2/l. In the experiments described below differences between the dissolved-oxygen concentrations of the light and dark bottles of less than 0·10 ml./l. were not considered significant. This corresponds to a carbon assimilation of 0·054 mg. C/l., which may be considered the lower limit of sensitivity of the method as here used.

In the ^{14}C experiments, it was found that if 1 ml. of ^{14}C stock were added to the sea water and the latter filtered immediately, the filtered material showed an activity which varied considerably but averaged 50 cpm. above the normal background of approximately 25 cpm. This activity persisted after the filter was washed with dilute HCl or exposed to HCl fumes, and was not removed by filtering the ^{14}C stock through a millipore filter immediately before the experiment. While its cause is not understood, it was found to be directly proportional to the activity of the ^{14}C stock and is believed to result from contamination. Because of the variability of this "blank", activities of less than 150 cpm. were not considered to be significant.

Assuming an average total carbon content of sea water of 24·5 mg./l., the lower limit of sensitivity of the ^{14}C method was therefore 0·0013 mg. C/l. or $^1/_{40}$th that of the oxygen method.

Experiments.

Three series of experiments were conducted in which the photosynthetic rates of various concentrations of *Nitzschia* were measured by the oxygen and ^{14}C methods for experimental periods of 6, 24, and 48 hours. *Nitzschia* concentrations were determined from hemacytometer counts and were expressed as the equivalent weight of carbon. The data for this conversion were obtained by centrifuging the cells from a one-litre culture of *Nitzschia,* of known cell-concentration, and drying to a constant weight at 60°C. The figure obtained ($3·2 \times 10^{-11}$ g./cell), although based upon a single analysis, showed good agreement with those of Riley (1943) and Ketchum and Redfield (1949) for the same organism. Using Ketchum and Redfield's elementary analysis of *Nitzschia,* its carbon content is 55 % of the dry weight, or $1·76 \times 10^{-11}$ g./cell.

Nitzschia concentrations in these experiments ranged approximately from 0·025 to 3·0 mg. C/l., which corresponds roughly with phytoplankton concentrations which might be expected in situations ranging from tropical ocean waters to coastal blooms (see Riley *et al.,* 1945, p. 44).

Photosynthesis rates are expressed as the weight of glucose-carbon synthesized per day, on the assumption of a 12-hour day-light day, and are illustrated in Figure 1.

Measurements of photosynthesis could not be made by the oxygen method at the lower concentrations of *Nitzschia* in the 6- and 24-hour experiments, since there was no significant difference between the dissolved-oxygen content of the light and dark bottles. At higher concentrations of the diatom, where photosynthesis could be measured by both methods, agreement between them was extremely good. In the 48-hour experiment, on the other hand, values obtained by the ^{14}C method were appreciably lower than those given by the oxygen method. This discrepancy is believed to be largely due to the uncorrected loss of ^{14}C by respiration, as discussed earlier. In 48 hours this may have represented a considerable fraction of the assimilated ^{14}C, particularly since the photosynthetic rate became reduced in the experiment. The

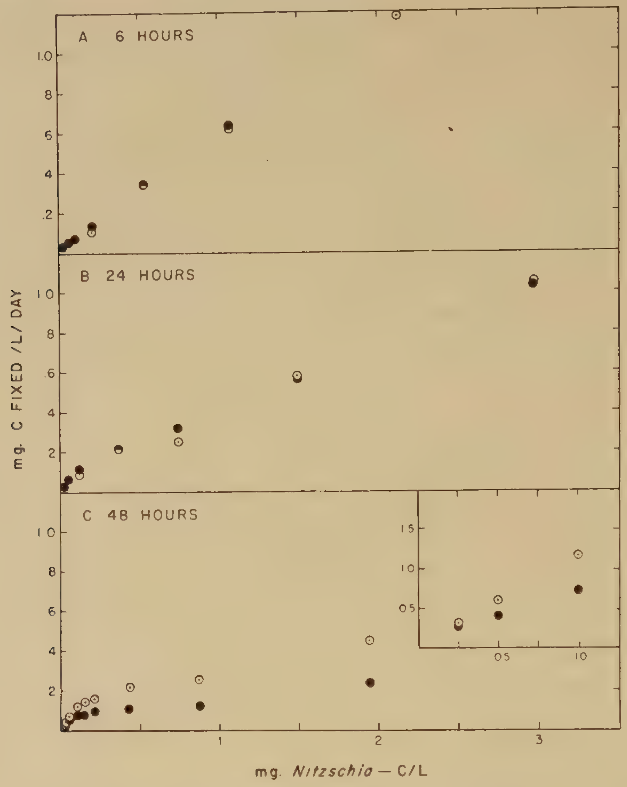

Figure 1. The relation between the concentration of *Nitzschia* and its rate of photosynthesis as measured by the oxygen method (open circles) and the ^{14}C method (closed circles).

discrepancy can hardly be attributed to an inaccuracy of the oxygen values, since any errors inherent in the oxygen method appear to result in the underestimation of photosynthesis.

The linear relationship between photosynthesis and diatom concentrations observed in the 6-hour experiment indicates that, within the range of concentrations studied, photosynthesis per unit of *Nitzschia* proceeded at a constant rate. In the 24-hour experiment, however, a decrease in the photosynthetic rate (mg. C fixed / mg. *Nitzschia*-C) was observed at a concentration of 0·125, but this rate then appeared to remain constant between 0·125 and 2·980 mg. C. In the 48-hour experiment, the steady decrease in the photosynthetic rate with increasing *Nitzchia* concentrations clearly indicates that nutrient exhaustion or some other factor became limiting to photosynthesis. Here the oxygen method gave measurable values for photosynthesis at the lower concentrations of the diatom and indicates a linear relationship between photosynthesis and concentration only within the range 0·025—0·100 mg. *Nitzschia*-C/l. (see insert in Figure 1, C).

A comparison of the photosynthetic rates observed in the three experiments of different duration is not advisable since the *Nitzschia* used in each experiment came from a different culture, which was in a different growth-phase. Riley (1943) has demonstrated that photosynthesis of *Nitzschia* varies considerably with its growth-rate.

Therefore, another experiment was conducted in which only one concentration of the diatom was used and photosynthesis was measured at different intervals of time, from 6 to 96 hours. In each case the rate of photosynthesis was determined for the entire experimental period and then calculated on a daily basis. To avoid the exhaustion of nutrients early in the experiment, a relatively low concentration of 0·14 mg. *Nitzschia*-C/l. was used.

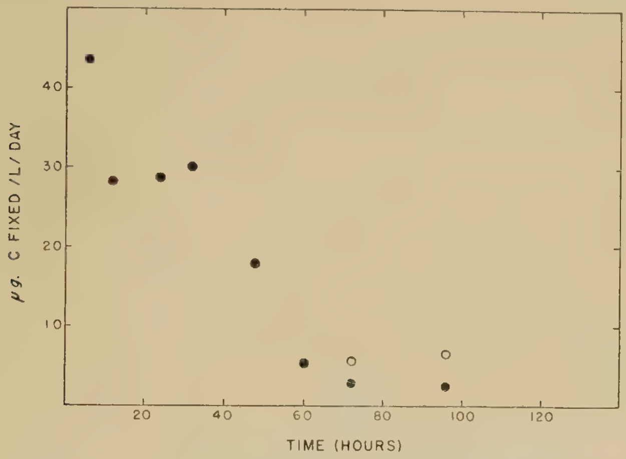

Figure 2. The relation between the duration of the experiment and the measurement of the photosynthetic rate of *Nitzschia* (0·04 mg. C/l.) by the oxygen method (open circles) and the ^{14}C method (closed circles).

The results of this experiment are illustrated in Figure 2. Here it is apparent that the photosynthetic rate as measured by the ^{14}C method decreased irregularly but definitely as the duration of the experiment increased, from 0·044 mg. C/l./day at 6 hours to 0·004 mg./l./day at 96 hours.

The oxygen method gave significant photosynthesis values only at 72 and 96 hours. These were considerably higher than the corresponding ^{14}C values measured at the same time, illustrating the loss of ^{14}C by respiration in the latter. However, the oxygen values were also much lower than the 6-hour ^{14}C value, indicating that an actual reduction of photosynthesis did occur.

A somewhat similar time-study was made using, in place of *Nitzschia*, raw sea water, containing its natural plankton, collected from Vineyard Sound in July 1953. This water was divided into two portions, the first of which was untreated, while the second was enriched with N, P, Si, and Fe. The photosynthetic rates occurring in both the

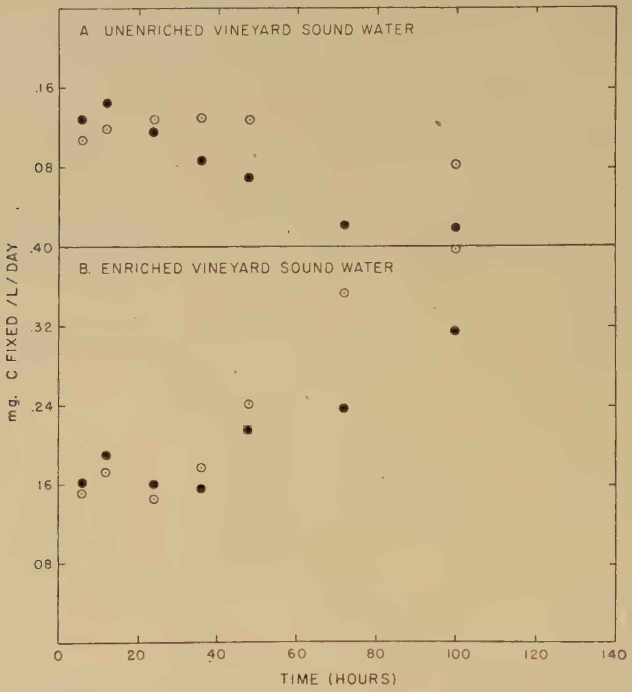

Figure 3. The relation between the duration of the experiment and the measurement of the photosynthetic rate of a natural plankton population by the oxygen method (open circles) and the ^{14}C method (closed circles).

enriched and unenriched water were measured by the two methods for periods of 6 to 100 hours and expressed as the rate per day, as in the preceding experiment (Figure 3).

In both enriched and unenriched water good agreement was observed between photosynthesis measurements obtained by the two methods from 6 to 24 hours. From 24 to 100 hours the ^{14}C method gave increasingly lower values than the oxygen method.

In the enriched water, both methods showed an increase in photosynthesis per unit of time as the experiment progressed, corresponding to growth of the contained phytoplankton. However, while photosynthesis per day measured by the oxygen method showed an increase of over 150 $^0/_0$ at 100 hours over that observed at 6 hours, a corresponding increase of only 100 $^0/_0$ was observed by the ^{14}C method.

In the unenriched water, the photosynthetic rate as measured by the oxygen method remained roughly constant for the entire 100 hours, while measurements by the ^{14}C method showed a steady decrease with time after 24 hours, with a photosynthetic rate at 100 hours less than 25 $^0/_0$ of that observed at 6 hours.

In this experiment, the discrepancy between the values obtained by the two methods is again believed to result principally from ^{14}C lost by respiration.

Discussion.

The experiments described above substantiate Steemann Nielsen's contention that comparable photosynthesis measurements may be obtained by both the oxygen and ^{14}C methods in eutrophic ocean waters. However, if photosynthetic rates are relatively low, use of the oxygen method is possible only if employed for rather long-term experiments (48 hours or more) while the more sensitive ^{14}C method may still usually find application in 6- to 12-hour experiments.

No evidence was found to substantiate Steemann Nielsen's claim that oxygen experiments conducted for periods of more than 24 hours give unrealistically high values. On the contrary, such values were often appreciably lower than those obtained by 6-hour ^{14}C experiments. This is undoubtedly due in part to errors inherent in the oxygen method, but is probably also a reflection of a real reduction of the photosynthetic rate which must inevitably occur over a period of time in an enclosed sample of sea water containing a limited supply of nutrients.

The ^{14}C method does not appear to be suitable for measuring photosynthesis in experiments of more than 24 hours duration, due to the loss of assimilated ^{14}C by respiration. As discussed earlier, this factor is undoubtedly affected by several variables and hence cannot be accurately estimated. The observed differences between photosynthetic rates obtained by the two methods in the experiments described above are believed to result from this source of error. Furthermore, the discrepancy between the two sets of data tends to minimize the error, since values obtained by the oxygen method were themselves probably somewhat lower than the true photosynthetic rates.

If ^{14}C experiments are limited to 24 hours or less, the loss of assimilated ^{14}C by respiration does not appear to be significant. In view of Steemann Nielsen's success in obtaining measurements of photosynthesis in tropical ocean waters with 6-hour ^{14}C experiments, the preceding discussion would appear to be of academic interest. However, these authors were unable to detect significant ^{14}C assimilation in the Sargasso Sea during August in 24-hour experiments under 1,500 foot-candles of illumination, using ^{14}C stock with an activity of $1{\cdot}39 \times 10^6$ cpm. While this difficulty might have been somewhat overcome by using ^{14}C of greater activity, the latter would increase errors caused by contamination, as discussed earlier, thereby reducing both sensitivity and accuracy. Thus conditions may exist in the oceans under which photosynthesis may not by accurately measured even by the ^{14}C method.

Summary.

1. Measurements of phytoplankton photosynthesis rates by the oxygen and ^{14}C methods gave comparable values in 6- to 24-hours experiments where photosynthetic activity was great enough to be measured by both methods.
2. Under conditions of reduced photosynthesis the more sensitive ^{14}C

method usually permitted measurements within 6—24 hours, while the oxygen method required an experimental period of several days.

3. Oxygen experiments of more than 24 hours duration gave values which compared favourably with those obtained from 6-hour ^{14}C experiments, provided that the rate of photosynthesis remained constant during the entire experiment. If nutrients or other factors became limiting to photosynthesis, such long-term experiments gave values appreciably lower than 6- to 24-hour measurements by either method.
4. ^{14}C experiments conducted for periods of more than 24 hours gave values considerably lower than oxygen experiments of the same duration, presumably due to the loss of assimilated ^{14}C by respiration. In the absence of sufficient information to correct for this error, the ^{14}C method is not recommended for use in long-term experiments.

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THE ECOLOGY OF PHYTOPLANKTON BLOOMS IN MORICHES BAY AND GREAT SOUTH BAY, LONG ISLAND, NEW YORK

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THE ECOLOGY OF PHYTOPLANKTON BLOOMS IN MORICHES BAY AND GREAT SOUTH BAY, LONG ISLAND, NEW YORK[1]

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In recent years Great South Bay and Moriches Bay have supported an extremely heavy growth of phytoplankton which characteristically appears early in the spring and persists throughout the summer and fall. At the peak of their growth, the contributing organisms have been found to exceed concentrations of ten million cells per ml., and the resulting turbidity may reduce Secchi disc transparency to less than one foot in places.

Records maintained since 1922 by Mr. J. B. Glancy show that the recurrent annual populations of algae in Great South Bay have consisted almost without exception of small, unicellular, green organisms 2–4 μ in diameter, which have been referred to locally as "small forms." This type of population differs greatly from the mixed communities of diatoms, green flagellates, and dinoflagellates which are typical of the plankton flora in other bays and estuaries of the same general region. Another striking feature is the persistence of the "small form" populations throughout the spring, summer, and fall, in marked contrast to the seasonal succession of dominant species which is commonly observed elsewhere. It is the purpose of this report to analyze the physiological factors which may account for the dominance of "small forms" in the recurrent plankton blooms.

These dense growths of algae have greatly reduced the value of the surrounding region as a recreational area, and are also considered to be the principle cause of the failure of what was formerly a prosperous oyster industry in Great South Bay. Correlated with and suspected as a cause of the algal blooms is the existence of a large duck industry which now consists of over 40 individual farms centered along the tributary streams and coves of Moriches Bay. These farms are so situated that their waste products eventually enter the bays, greatly enriching the water and presumably creating conditions conducive to the development of the plankton blooms.

The results of a study of various aspects of the hydrography, chemistry, and biology of Great South Bay and Moriches Bay, will appear elsewhere (Ryther, unpublished data). This investigation has revealed that the embayments under consideration represent a unique ecological environment which results partly from pollution contributed by the surrounding duck farms, and partly from the topographic and hydrographic features of the area. The pollution not only provides an extensive fertilization of the bay waters with nutrients essential to phytoplankton growth, but, in addition, the presence of organic nitrogen compounds and the low ratio of nitrogen to phosphorus in the pollutants create conditions which differ considerably from the chemical composition of natural sea water. The shallow nature of the embayments contributes to the development of abnormally high water temperatures which may reach 30° C. during the summer months. Their extremely low flushing rate results in the retention for long periods of time of both the pollutants and their entraining fresh water, which further builds up the concentrations of nutrients and the resulting phytoplankton crop and also reduces salinities to approximately 50% of normal sea water in the open embayments and less than 10% in the estuaries.

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[1] Contribution No. 685 from the Woods Hole Oceanographic Institution.

This report includes the results of experiments performed with the two dominant species of "small forms," and, for contrast, with the common neritic diatom, *Nitzschia closterium*. Growth rates of these algae were studied in relation to the temperature, salinity, and nutrient conditions peculiar to Great South Bay and Moriches Bay as described above. The results of these experiments were then related to the distribution of the "small form" population and associated physical and chemical conditions existing in the embayments.

The author expresses his sincere thanks to Mr. J. B. Glancy, the Messrs. G. H. Vanderborgh, Sr., and Jr., and the New York State Department of Conservation for their generous assistance in providing laboratory and boat facilities in the field. Appreciation is also tendered to Dr. Wm. Butcher and Dr. R. A. Lewin for their help in the identification of the phytoplankton. The investigation was carried out, in part, with the assistance of a grant from the National Science Foundation.

CULTURE METHODS

The "small form" population of 1952 and 1953 consisted principally of two species of algae. That which was the more numerous was identified by Dr. Wm. Butcher as his recently described *Nannochloris atomus* (Butcher, 1952). The other species was tentatively placed by Dr. Ralph Lewin in the genus *Stichococcus*, possibly *S. cylindricus* Butcher.

Because of their similarity of appearance, it was impossible to distinguish between the two species in routine examinations of the natural population. Consequently they will be considered together as a single community and referred to collectively as the "small form" population.

The *Nannochloris, Stichococcus,* and *Nitzschia* used in the experiments were isolated from water samples collected from Great South Bay. Pure cultures were obtained by the agar streak method incorporating the use of penicillin (200 units/ml.) and streptomycin (10–20 units/ml.) in the enriched agar. Colonies isolated from streaks were transferred several times on the antibiotic agar and then inoculated into liquid media.

Pure cultures were used in all experiments involving nutrient studies, while cultures of *Nannochloris* and *Stichococcus* used in the temperature and salinity experiments were unialgal but not bacteria-free.

Growth studies were made with algal cultures grown in 300 ml. of media in 500-ml. Erlenmeyer flasks. Lighting was provided by a bank of mixed daylight and white fluorescent lamps which produced 500 foot candles of illumination.

Temperature was controlled by keeping cultures immersed in running tap water, which provided a range of 20–30° C. over a six-months period by varying the rate of flow of the water. This method permitted control to ± 2° C. for periods of one to two weeks, the normal duration of the experiments. Cultures grown at temperatures of 5–15° C. were maintained to a variability of ± 1° C. in an illuminated, constant temperature box. Except where the effect of temperature upon growth was being studied, cultures were routinely grown at 18–22° C.

The same basic medium was employed for the culture of all three species of algae, and consisted of a modification of the artificial sea water of McClendon *et al.* described in Sverdrup, Johnson and Fleming (1942), enriched with N, P, Si, and Fe. At full strength ($34.62^0/_{00}$) it consists of the following, in parts per thousand:

NaCl	26.726	H_3BO_3	0.058
$MgCl_2 \cdot 6H_2O$	2.260	$Na_2SiO_3 \cdot 9H_2O$	0.020
$MgSO_4 \cdot 7H_2O$	3.248	NH_4Cl	0.053
$CaCl_2$	1.153	$Na_2HPO_4 \cdot 12H_2O$	0.020
KCl	0.731	Fe Citrate	0.001
$NaHCO_3$	0.198		
KBr	0.058		

Since the growth of *Nitzschia* is relatively poor in ammonia-nitrogen, as will be demonstrated, NH_4Cl was replaced with $0.10^0/_{00}$ KNO_3 in media used for growing the diatom. Several of the other constituents have been altered in concentration or replaced with other ingredients in the various experiments, as will be discussed below.

Growth in all experimental cultures was determined by cell counts with a Levy hemacytometer. Cultures were grown for periods of 10 days to two weeks, and cell counts were made at intervals of two to three days.

The growth rate, expressed as divisions per day (*d*), was calculated for the entire period of growth from the expression:

$$d = l_n \frac{C_t}{C_o} \times \frac{1}{t\, l_n 2},$$

where C_t and C_o are cell concentrations at times *t* and *o*, respectively.

EXPERIMENTS AND THEIR APPLICATION TO FIELD OBSERVATIONS

1. *Nutrients*

A. Experiments

A series of laboratory experiments was conducted to determine the relative growth rates of *Nannochloris*, *Stichococcus*, and *Nitzschia* in each of several different forms of nitrogen. Pure cultures of the three species were used, and each was grown at its optimum salinity, as will be discussed in a later section. All three algae were grown in media containing one mg. atom per liter of nitrogen in each of the following forms: nitrate, nitrite, ammonia, urea, uric acid, l-cystine, asparagin, and glycocoll. The resulting growth rates, in divisions per day, are given in Table I.

TABLE I

The effect of the nitrogen source upon the growth rates of Nannochloris, Stichococcus, and Nitzschia

Nitrogen source (1 mg. A N/L)	Growth rate: Divisions per day		
	Nannochloris	*Stichococcus*	*Nitzschia*
NO_3	0.54	0.57	0.37
NO_2	0.65	0.57	0.40
NH_3	0.72	0.61	0.04
Urea	0.62	0.56	0.21
Uric acid	0.68	0.59	0.23
l-cystine	0.77	0.62	0.00
Asparagin	0.68	0.62	0.15
Glycocoll	0.66	0.61	0.07

It may be seen that the diatom grew about equally well in nitrate and nitrite, poorly in ammonia, and slowly or not at all in the organic N compounds. Both *Nannochloris* and *Stichococcus* showed good growth in all of the forms of nitrogen tested. However, the growth rate of both species in nitrite and nitrate was slightly lower than that in ammonia, and, in general, was less than growth rates in the organic compounds. The best growth of *Nannochloris* was observed in cultures containing l-cystine.

TABLE II

The effect of the N:P ratio upon the growth rates of Nannochloris, Stichococcus, and Nitzschia

N:P ratio (by atoms)	Growth rate: Divisions per day		
	Nannochloris	*Stichococcus*	*Nitzschia*
15:1	0.68	0.53	0.39
5:1	1.32	0.88	0.40

In another series of experiments, growth rates of the three species of algae were determined in media containing the same concentrations of nitrate-nitrogen (one mg. atom per liter) but two different concentrations of phosphate-phosphorus (0.066 and 0.200 mg. atoms per liter). By varying the concentrations of phosphorus in this manner, the resulting N : P ratios by atoms in the two media were 15 : 1 and 5 : 1, respectively.

In this experiment, increasing the P concentration, or lowering the N : P ratio, had no effect upon the growth of the diatom, *Nitzschia*, but approximately doubled the growth rates of *Nannochloris* and *Stichococcus* (Table II).

B. Application to field observations

Richards (unpublished data) measured the nitrogen present as uric acid, ammonia, nitrite, and nitrate in the duck farm effluents, the tributaries to Moriches

Bay receiving these effluents, and in Moriches and Great South Bays on August 21, 1952. His analyses showed that uric acid could be detected only in the duck farm effluents, ammonia was present in both the effluents and the tributary streams, while nitrite and nitrate were found nowhere except as traces. No appreciable concentrations of inorganic N in any of the forms tested for was found in either Moriches Bay or Great South Bay.

Phosphorus, on the other hand, appears to have been present in excess of the requirement of the phytoplankton during most of the year, not only in the polluted estuaries, but also throughout the bay waters. Filtered water samples collected from several locations in Great South Bay and Moriches Bay failed to support the growth of *Stichococcus,* if untreated or enriched with phosphate. However, dense growth of the alga occurred in all samples if enriched with ammonia-N indicating that the latter was the principal limiting factor to the growth of the algae population.

The population maxima normally occurred in Moriches Bay and its polluted tributaries. The distribution pattern of the organisms in Great South Bay and Shinnecock Bay is strongly suggestive that their presence in these waters was largely the result of the seaward flushing of Moriches Bay water, and that growth was principally confined to an area close to the source of the nutrient rich duck farm pollutants.

In its original state in the duck wastes, nitrogen occurs as excreted uric acid and amino compounds contained in the undigested food residues. Investigations in this laboratory by Vaccaro, Norton and Plunkett (unpublished) have disclosed that bacteria present in the duck farm effluents are capable of decomposing uric acid with great rapidity. In water samples collected from these effluents, the contained uric acid was found to decrease to 10% of its original concentration in an average of 15 hours at 2° C. The nitrogenous end products of this decomposition were not investigated, but Copeman and Dillman (1937) observed that the decomposition of the uric acid of guano in water was accompanied by an increase in ammonia from 32.2% to 85.0% of the total nitrogen in four days.

According to the classical concept of the nitrogen cycle of the sea, the decomposition of organic nitrogen to ammonia is followed by the nitrification of the ammonia to nitrite and nitrate. This phase of the cycle appears never to occur to any appreciable extent in the Moriches Bay area. Since nitrogen is the limiting factor to the growth of the phytoplankton, it is utilized as quickly as it becomes available and before decomposition to nitrite and nitrate can occur.

It follows that those organisms will have a distinct advantage which are able to utilize the nitrogen in the earliest stages of its decomposition. The laboratory experiments have demonstrated that *Nannochloris* and *Stichococcus* are particularly well adapted to growth in organic nitrogen and its early decomposition products. In contrast, the diatom, *Nitzschia closterium,* grew poorly or indifferently in these N forms. The advantage of the "small forms" over the latter in the Moriches Bay environment is therefore obvious.

Nitrogen and phosphorus are contained in duck faeces at a ratio of approximately 3.3 atoms of nitrogen to one atom of phosphorus. Total N and total P data from the tributaries of Moriches Bay and from the bay itself show N : P ratios ranging from 2.3 : 1 to 4.4 : 1 (Richards, unpublished data). Approximately one-half of the total phosphorus consisted of inorganic phosphate in these analyses. On the other hand, no appreciable concentrations of available nitrogen were found anywhere in the bay waters, as previously discussed. If it is assumed that half of the total phosphorus and all of the total nitrogen were incorporated in particulate matter, which consisted principally of algal cells, then the N : P ratio of the phytoplankton would range from 4.6 : 1 to 8.8 : 1 by atoms.

Various authors have pointed out that the ratio of nitrogen to phosphorus in open ocean water is rather constant at approximately 15 : 1 by atoms, which is closely reflected in the ratio of these elements in marine phytoplankton (Redfield, 1934; Cooper, 1937, 1938; Fleming, 1940). Harvey (1940) found that natural populations of diatoms utilized about 20 atoms of nitrogen to one atom of phosphorus.

Ketchum and Redfield (1949) showed that laboratory cultures of *Nitzschia closterium* contained N and P at a ratio of 11.6 : 1, but cultures of six species of Chlorophyta, including *Stichococcus bacillaris,* had N : P ratios ranging from 3.5 : 1 to 6.6 : 1, or two to three times as much phosphorus per atom of nitrogen as the diatoms. This compares favorably with the estimated N : P ratio of the phytoplankton of Moriches Bay which consisted predominantly of the Chlorophyta, *Stichococcus* and *Nannochloris.*

These data indicate that there is a basic difference between the chemical composition of the green algae, typical of fresh and brackish water, and oceanic diatoms, at least with respect to the N : P ratio in the cells. The growth studies bear out this contention by demonstrating the fact that the Chlorophyta grow much more rapidly in water containing three times as much phosphorus per atom of nitrogen as normal sea water, while this increase in phosphorus has no effect upon the growth of the diatom, *Nitzschia closterium.*

The N : P ratio of the polluted water of Moriches Bay and its environs thus appears to be another factor favoring the growth of the "small forms" and their competition with organisms similar to *Nitzschia* in their nutritional requirements.

2. *Salinity*

A. Experiments

To determine the effect of salinity upon the growth rates of *Nannochloris, Stichococcus,* and *Nitzschia,* each species was grown in a series of dilutions of the artificial medium described above. This series consisted of 100, 75, 50, 25, and 1 per cent solutions of the indicated concentrations of NaCl, $MgCl_2$, $MgSO_4$, $CaCl_2$, and KCl. The concentrations of the other ingredients, which together account for less than $0.5^0/_{00}$, were not altered to avoid possible deficiencies of those nutrients.

The salinities of the resulting solutions, in $^0/_{00}$, totaled, respectively, 34.51, 25.91, 17.44, 8.91, and 3.80, with an additional $0.048^0/_{00}$ in each of the *Nitzschia* media as a result of replacing NH_4Cl with KNO_3.

These experiments indicate a salinity optimum at or near that of full sea water for *Nitzschia,* a typical marine species, while the "small forms" grow well within a wide range of salinities, with optima at about 50% sea water, and may be considered as brackish water species (Table III).

TABLE III

The effect of salinity upon the growth rates of Nannochloris, Stichococcus, and Nitzschia

Salinity: $^0/_{00}$	Growth rate: Divisions per day		
	Nannochloris	*Stichococcus*	*Nitzschia*
34.51	0.45	0.44	0.40
25.91	0.61	0.55	0.34
17.44	0.69	0.61	0.28
8.91	0.56	0.58	0.09
3.80	0.37	0.52	0.00

B. Application to field observations

The highest concentrations of "small forms" normally occurred in Moriches Bay in water of approximately $15^0/_{00}$ salinity, or close to the physiological optima of the organisms. While this does not imply that salinity was the factor controlling the distribution of the phytoplankton, particularly in view of the preceding discussion concerning the distribution of nutrients, it nevertheless represents another environmental condition favoring the growth of the "small forms" over that of the more typical marine forms.

Of still greater importance, however, is the fact that *Nannochloris* and *Stichococcus* were able to grow remarkably well within the entire range of salinities tested in the experimental cultures, in contrast to the diatom, which was unable to grow at all in the low salinity cultures. This is particularly significant in view of the wide range of salinities which were observed in Great South Bay and Moriches Bay and their tributaries. Over a million "small forms" per ml. were present throughout the late spring and summer in the upper Forge River, directly opposite a group of duck farms, in water of less than $1^0/_{00}$ salinity. In addition, evidence was obtained in the experiment described in Section 1B that nitrogen-enriched water from Fire Island Inlet ($26^0/_{00}$ salinity) was able to support a prolific growth of *Stichococcus.*

The population which thus becomes established in the highly enriched rivers and estuaries is able to continue growth as it is borne out to sea until its source of nutrients becomes depleted. At no time does salinity limit its growth and thereby permit the succession of other forms.

3. Temperature

A. Experiments

Growth rates of the three algae were determined for cultures grown at temperatures ranging from 5° to 30° C. at intervals of 5° (Table IV). *Nitzschia* was grown in the full strength artificial medium ($34.51^0/_{00}$) while the "small forms" were grown in the half-strength media ($17.44^0/_{00}$) found to give optimum growth in the preceding section.

The diatom multiplied within a temperature range of 5–25° with optimum growth at 15°. Its division rate was relatively high at the lower limit of 5°, but decreased rapidly above 20°.

No appreciable growth of *Nannochloris* or *Stichococcus* occurred at temperatures of 10° or lower, but both species grew rapidly at temperatures of 15–30°. No clear-cut optimum could be detected between 15° and 25°, but growth rates of both "small forms" decreased considerably at 30°.

B. Application to field observations

When field studies were begun on April 1, a mixed diatom bloom occurred in the bays, which consisted of 890,000 *Leptocylindrus minimus,* 35,000 *Thallasiosira nana,* and 12,000 *Skeletonema costatum* per ml. at a station in central Moriches Bay. There were also present at that time 211,000 "small forms" per ml. On May 13 the situation was reversed, with "small forms" dominating the plankton and diatoms reduced to a total of 40,000 cells per ml. The latter subsequently disappeared from the plankton and did not reappear until the following February.

The principle cause of this succession of dominants appears to be temperature. Experimental evidence has shown that *Nannochloris* and *Stichococcus* are unable to grow appreciably at the 10° temperature which prevailed throughout the embayments on April 1, while the diatom, *Nitzschia,* maintained a relatively high growth rate at temperatures as low as 5°.

During the period of May–September, temperatures in Moriches Bay ranged from 13° to 30°. The growth experiments demonstrated that both *Nannochloris* and *Stichococcus* divide rapidly within that temperature range. The seasonal distribution of inorganic phosphorus in the Forge River at a station close to the source of pollution indicates that the heaviest enrichment of the bay waters also occurred during the same period of May–September. The situation therefore exists that during that part of the year when the bay is most heavily enriched with nutrients, temperatures may be expected which will fall approximately within the range for optimum growth of the "small forms."

The month of July, 1952, was characterized by abnormally high temperatures throughout the Long Island area. Water temperatures of the three embayments under consideration ranged from 28–30° during the July 22–23 survey. A

Table IV

The effect of temperature upon the growth rates of Nannochloris, Stichococcus, and Nitzschia

Temperature: ° C.	Growth rate: Divisions per day		
	Nannochloris	*Stichococcus*	*Nitzschia*
5	0.00	0.00	0.29
10	0.14	0.12	0.42
15	0.65	0.48	0.48
20	0.80	0.48	0.40
25	0.71	0.43	0.19
30	0.32	0.26	0.00

decrease in the "small form" population at that time was generally observed throughout the area. This may be explained by the fact that the July temperatures exceeded the optima of the "small forms." The division rates of both *Nannochloris* and *Stichococcus* at 30° were observed to be approximately one half of that at 25° (Table IV). This population drop was obviously not associated with a nutrient depletion, as indicated by unusually high inorganic phosphorus concentrations on that date.

The presence of relatively large numbers of "small forms" between October and April, when temperatures were presumably too low to permit their growth, may be explained on the basis of the slow flushing time of Moriches Bay and the low death rate of the organisms. This subject will be discussed at length elsewhere. It is significant, however, that the slow rate of disappearance of the static population during the winter months not only accounts for the presence of the organisms during that part of the year when they are unable to grow, but it also provides for a substantial seed population by the following spring, when conditions again become favorable for growth. The latter may be one of the chief reasons for the annual recurrence of the "small form" populations.

DISCUSSION

The "small forms," *Nannochloris* and *Stichococcus,* have been found to be particularly well adapted for growth under the peculiar physical and chemical conditions which occur in Great South Bay and Moriches Bay. In addition, it has been brought out that the slow flushing time of the bay waters allows for the retention of a considerable fraction of the summer bloom during the unproductive winter months, thereby providing for a substantial seed population on the following spring. This combination of circumstances alone is perhaps sufficient to account for the presence of "small form" blooms in these waters every year.

It is significant, however, that ecological conditions not only approach an optimum for the growth of the "small forms" but are also quite unsatisfactory for the development of the diatom, *Nitzschia closterium.* It is perhaps suggestive that the physiological characteristics of *Nitzschia* considered here are representative of diatoms, dinoflagellates, and other plankton flora normally found in unpolluted estuaries. While this provides a convenient hypothesis, such an assumption is unwarranted on the basis of the existing evidence.

The utilization of ammonia and amino acids by the green algae has been described by many workers (Schreiber, 1927; Braarud and Føyne, 1930; Algéus, 1946, 1949, 1950, and other papers). If diatoms in general are similar to *Nitzschia* in the matter of their nitrogen utilization, their absence from the summer blooms of Moriches Bay could be explained on that basis alone. This, however, does not appear to be the case.

Harvey (1940) found that natural populations of mixed diatoms could utilize nitrogen as nitrate, ammonia, urea, uric acid, and several amino acids, and that the growth of some species appeared to be better in ammonia than in nitrate. Chu (1943) observed that several diatoms (*Nitzschia palea, Fragilaria crotonensis, Asterionella gracillima*) grew equally well in ammonia or nitrate.

A recent paper by Harvey (1953) describes the exponential growth of *Nitzschia closterium* cultures in media containing ammonia as a source of nitrogen. Since this is contradictory to the results of the experiments described in this paper, in which *Nitzschia* was found to grow very poorly in ammonia, these experiments were repeated, using both the artificial medium and natural sea water containing one mg. atom per liter of ammonia as a nitrogen source. The growth of *Nitzschia* in both of these media was equally as poor as that reported in the earlier experiments. Since the concentration of ammonia used here was probably higher than that employed by Harvey, there is the possibility that this was the factor which was toxic to the diatom (see Algéus, 1946) although it obviously was not so for either *Nannochloris* or *Stichococcus*. It is equally plausible that the *Nitzschia* used by Harvey and the present author represented different physiological varieties.

From the existing evidence of both the laboratory and the field observations, it appears that the only time of the year when organisms other than the "small forms" are able to dominate the phytoplankton is that period during which temperatures are too low to permit the growth of the Chlorophyta. In this respect, however, the natural situation in the bay waters differs somewhat from that which might be expected from the culture work. The experiments have shown that the "small forms" are able to grow very slowly if at all at the temperatures observed in the bays after October, while diatoms did not begin to flourish there until February. Although the bays were heavily enriched only during the duck growing season, relatively high concentrations of nutrients appear to be present throughout the year, presumably from the decomposition of the rich sediments in the tributaries receiving the duck farm effluents.

A remaining possibility exists that the absence of diatoms and other forms from the water between October and February may have been due, in part, to the production of inhibitory substances by the "small forms" and the accumulation of these products in the bay waters. This is suggested by the work of Pratt and his group (1944, and earlier papers) who found that *Chlorella* produces an antibiotic which inhibits its own growth, and by experiments of Rice (1949) who demonstrated that *Chlorella* and *Nitzschia frustrulum* produce substances which are mutually inhibitory.

Lefèvre and his co-workers (1951) have further shown that filtrates of both laboratory cultures and of pond water containing blooms of different species of algae produce inhibitory effects upon a wide variety of phytoplankton organisms.

It is perhaps significant that Pratt's group (Pratt, Oneto and Pratt, 1945) found that the maximum inhibitory effect of Chlorella was produced by senescent, non-dividing cultures, typical of the late fall and winter population of "small forms" in Great South Bay and Moriches Bay.

SUMMARY

1. The phytoplankton bloom in Great South Bay and Moriches Bay during the spring, summer, and early fall of 1952 consisted of the Chlorophyta, *Nannochloris atomus* and *Stichococcus* sp., to the virtual exclusion of other species. These organisms persisted throughout the year, but were accompanied by minor diatom blooms during the winter and early spring.

2. Growth rates of *Nannochloris, Stichococcus,* and the diatom, *Nitzschia closterium* were determined from laboratory cultures grown under various conditions

of temperature, salinity, and nutrients which are peculiar to the Great South Bay-Moriches Bay area.

3. *Nannochloris* and *Stichococcus* grew well in nitrogen present as nitrate, nitrite, ammonia, urea, uric acid, cystine, asparagin, and glycocoll. *Nitzschia* grew equally well in nitrate and nitrite, but showed poor growth in ammonia and the organic N compounds.

4. *Nannochloris* and *Stichococcus* grew approximately twice as fast in media containing an N : P ratio of 5 : 1 as they did in media with a 15 : 1 ratio of these elements. The growth rate of *Nitzschia* was the same in both media.

5. *Nannochloris* and *Stichococcus* appear to be brackish water forms with salinity optima of about $17^0/_{00}$, but both species grew well within a salinity range of $3\text{–}34^0/_{00}$. *Nitzschia,* a typical marine form, was unable to grow in low salinity water.

6. *Nannochloris* and *Stichococcus* grew at temperatures of 10–30° C., with very slight growth at 10° and an optimum range of 15–25°. *Nitzschia* grew within a temperature range of 5–25° with its best growth at 15°.

7. Pollution from duck farms bordering Moriches Bay heavily enriches the bay waters with plant nutrients. The presence of organic nitrogen compounds and the low ratio of nitrogen to phosphorus in the pollutants favor the growth of *Nannochloris* and *Stichococcus* over that of the more typical estuarine phytoplankton.

8. The peculiar nature of the pollutants together with low salinities and high water temperatures occurring at the time and place of maximum enrichment of the bay waters are factors which may explain the persistent dominance of the *Nannochloris-Stichococcus* community in the annually recurring plankton blooms in Great South Bay and Moriches Bay.

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MINERAL NUTRITION OF PHYTOPLANKTON[1,2]

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General Discussion

Many studies of the nutrition of phytoplankton have been initiated in an attempt to understand the ecological conditions suitable for their growth. Simultaneously, the advantages of algae as tools for physiological research, primarily in photosynthesis, were recognized, and many studies of nutrition were designed to provide suitable and reproducible cultures for these purposes. More recently the possibility of the use of organic material from algae as a source of food has stimulated extensive studies of mass cultures.

Because of the different viewpoints of investigators studying the nutrition of unicellular algae a variety of approaches have been used, which makes it difficult to compare the results. It seems worthwhile, therefore, to attempt to define more precisely four ways in which nutrient requirements have been studied and expressed. These are the absolute, the normal, and the minimum requirements for nutrients and their optimum concentrations.

The *absolute requirement* for a nutrient is based upon the postulate that the algae cannot grow, reproduce, or photosynthesize if the nutrient is lacking from the environment, and that no other nutrient can be substituted for it. It is basic to the understanding of the ecology and to the development of culture media since it determines the quality of the environment required. Hutner *et al.* (68) have discussed the value of chelating agents and suggest a rigorous technique for establishing absolute requirements in microbial nutrition.

The *normal requirement* is the quantity of each nutrient contained in cells produced during active growth of a population while no nutrient is limiting. This requirement is based upon the postulate that there is an ideal or normal composition of the cell, and that the algae tend to produce such cells if the environment permits. The normal requirement is as yet, and may always be, ill-defined because of the variability of composition of phytoplankton. However, the cells, by selective absorption, may assimilate a large proportion of an element in limited supply, without assimilating more than a small proportion of a nutrient present in excess. Variations in the composition of the cells thus tend to be less than variations in the composition of the medium. It should be possible to design a balanced medium from which all nutrients are removed at equal rates relative to their concentrations, so that the cells produced would be of the same relative nutrient composition as the

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[1] The survey of the literature pertaining to this review was concluded in August, 1953.

[2] Contribution No. 687 from the Woods Hole Oceanographic Institution.

medium. Such cells could be defined as "normal" cells. The normal requirements for *Chlorella*, as given below, indicate that, for every 100 parts by weight of carbon, about the following amounts of other major nutrients are required: N—15; P—5; Mg—2.5; K—1.8; S—1.6.

The *minimum requirement* is the quantity of a nutrient in the cell when the nutrient is limiting the growth of the population, all other nutrients being present in excess. It determines the mass or number of cells which can be produced for a given quantity of a nutrient, provided light or some other environmental factor does not limit the growth of the population. Cells containing this minimum quantity are deficient cells which would contain a greater amount if it were available. Algae deficient in nitrogen and phosphorus can be produced in this way, and these are capable of assimilating the nutrient from an enriched medium in the dark (59, 71, 106). This technique has been valuable in studying the internal metabolism of these nutrients (28, 86, 119, 120).

The optimum concentration or range of concentrations will permit the maximum rate of growth, reproduction, or photosynthesis of an algal population. It is not certain that the same concentration will be optimal for these three criteria. The optimum concentration is based upon the concept that too low a concentration may be limiting as a result of a decreased rate of assimilation, and that too high a concentration may be inhibitory or toxic. The lower limit may sometimes be confused by the complete removal of the nutrient from the medium as a result of growth of the population. This would be an indication of the minimal requirement rather than of a suboptimal concentration. Ideal studies of optimum concentrations would provide a constant environment by a continuous flow (85) or diffusion system (106) to eliminate the possibility of exhaustion.

The study of these nutritional requirements necessitates the use of pure or, at least, unialgal cultures. All requirements can be determined by cultures and absolute requirements can be established only by cultures. However, very few species have been obtained in pure culture compared to the enormous number of species found in the natural environment, and some species have proved difficult, others impossible to obtain in culture in the present state of our knowledge. Bold (12) lists, with references to original publications, over 200 genera of algae which have been cultured in the laboratory. Of these 82 genera include planktonic algae which are distributed as follows among major groups: 9 Myxophyceae, 39 Chlorophyceae, 6 Euglenaphyceae, 5 Heterokontae, 8 Dinoflagellatae, and 15 Bacillareae.

Most of the investigations of nutrition, however, have been made on the species of algae which are easy to culture. It is obvious that these algae may differ in nutrition and physiology from those which are difficult to culture, and this may be the clue to the difficulty. Presumably, if enough were known concerning their nutrition, these species could also be cultured. In the meantime, evidence from the composition of natural collections and the changes in the environment which result from their growth may produce clues which will ultimately make their culture and better knowledge of their nutrition possible.

Evidence from the chemical composition of natural populations has the advantage of giving relative proportions in which the nutrients were assimilated under specific conditions of growth. When the conditions of growth are known such analyses are valuable in determining the normal and minimal requirements. If complete, the analysis will include all the nutrients required for growth, but it cannot establish an absolute requirement since the cells may accumulate elements which are unnecessary. Such evidence is, therefore, suggestive of the necessity and proportions but is not conclusive evidence for the requirements.

The changes in nutrient salt concentrations in the environment permits studies of the rates of absorption of nutrients, and will show when the nutrient is approaching limiting concentrations. This type of observation has been made extensively in surveys of natural environments. When the minimum requirement for the population is known the determination of available nutrients may indicate the productive capacity of the environment. Armstrong & Harvey (5) have used the total phosphorus content of the water of the English Channel as a measure of its capacity to produce phytoplankton.

Normal requirements of marine populations have also been determined by the changes of the nutrient salts in nature. It was observed by Harvey (51, 56) and Redfield (104) that both nitrate-nitrogen and phosphate-phosphorus are completely removed from the surface water of the sea at about the same time as a result of the growth of phytoplankton. Redfield correlated the changes in these elements in the sea water and concluded that the ratio C:N:P of removal was 100:16.7:2.5 gm. Similar average proportions were observed by analysis of collections of plankton. Fleming (33) has collected analyses of plankton and presents a table of "plankton equivalents" which interrelate various physical and chemical properties of phytoplankton communities. For the study of the ecology of plankton production in the sea, these ratios have been of great value, and are comparable to, though much less precise than, the combining proportions of chemistry.

As early as 1896 Molisch (80) stated that the mineral nutrition of the algae was not unlike that of higher plants. This general conclusion has been reaffirmed many times. The major absolute requirements include carbon, nitrogen, phosphorus, sulphur, potassium, and magnesium. Iron and manganese are required in smaller amounts, sodium is not essential, and the evidence for a requirement for calcium is contradictory. Silicon is a major requirement for diatom growth but is unnecessary for other forms. Various other elements such as zinc, boron, cobalt, molybdenum and copper may be necessary as trace elements. These are frequently supplied by adding such solutions as Arnon's (6). In the sea, and in most lakes, all of the major elements are present in excess with the exception of nitrogen and phosphorus. The specific requirements for these elements will be discussed below.

Many different types of nutrient media have been developed for culturing algae. There is no general agreement concerning a best medium, nor do the media designed for different groups of algae vary more than the media designed by different investigators for the same alga. As Pringsheim (102, p. 32) points out

> Most algae are not affected by minute changes in the composition of the medium, otherwise they could not live under natural conditions. Changes effected by the algae themselves are often more decisive than differences between various media.

In general the media can be divided into two major types, those which are added to enrich natural waters and completely synthetic media made up entirely of purified salts and distilled water. The complete composition can be known only of the second type since the natural waters may add essential nutrients omitted in the enrichment solutions. Some of the media have obviously been designed to simulate natural conditions as closely as possible while others were apparently designed to produce a large population. Table I represents the major constituents of some of the synthetic media. These have been selected solely to indicate the range of concentrations which have been used and not because of their suitability or general use. Rodhe's (106) and Chu's (19) media were designed to simulate natural conditions and the contents of the various salts were adjusted as a result of physiological experiments on, respectively, the green algae *Ankistrodesmus falcatus* and *Pediastrum boryanum* and the diatom *Asterionella gracillima.* Tanada's (121) medium was also used for a diatom, *Navicula minima*, and that of Gerloff, Fitzgerald & Skoog (40, 41) was used successfully for the culture of 22 species of blue green algae. The media of Witsch (125), Scott (110), Myers & Clark (85), and Craig & Trelease (27) have all been used for the

TABLE I

CONCENTRATION OF MAJOR NUTRIENTS (MG. PER LITER) IN VARIOUS CULTURE MEDIA

	Ca	Mg	K	Na	S	N	P	Fe	Mn	Si
Rodhe (106)	14.7	1.0	2.2	7.5	1.3	10.2	0.89	0.18	0.01	4.6
Chu (19)	2.0	2.4	24.0	2.0		5.0	18.0	0.8		1.8
Chu (19)	91.0	7.6	18.7			17.0	9.0			9.1
Tanada (121)	0.3	6.1	399.0	1.8	8.4	87.0	64.0	0.18	24.0	
Gerloff, *et al.* (41)		0.13	2.25		0.8	13.6	0.45	0.03		
Witsch (125)	12.2	9.8	100.0		13.0	106.0	34.0	3.5		
Scott (110)	244.0	50.0	202.0		66.7	171.0	57.0	4.4	1.0	
Myers & Clark (85)		240.0	820.0		323.3	168.0	279.0	7.0	0.5	
Craig & Trelease (27)		486.0	1680.0	2.0	640.0	350.0	558.0	0.55	0.44	0.06
Geoghegan (39)		486.0	1320.0	2.0	1240.0	305.0	558.0	0.55	0.44	0.06

mass culture of *Chlorella* and are arranged in order of increasing total molarity which ranges from 6 to 64 millimols per liter. Geoghegan's (39) medium is derived from that of Craig and Trelease, but uses ammonium rather than nitrate-nitrogen. These media provide a wide range of total concentration and of each individual salt. The ratio of nitrogen to phosphorus, for example, in the various media used for *Chlorella* varies five-fold. The fact that luxurious growth of *Chlorella* is possible in these media emphasizes its marked adaptability to variations in environmental conditions.

Some algae which will not grow on completely synthetic media will grow when soil extracts, yeast extracts or other complicated mixtures are added. Sometimes the use of natural water in place of distilled water renders a medium suitable. Pringsheim has used soil and peat extracts extensively and effectively in obtaining growth of cultures and has recently (102) reviewed their value. He concluded that these may act through providing trace elements or organic growth factors or because the humic acids may form complexes with essential elements keeping them present in an available form.

The use of chelating compounds in culture media has been introduced by Hutner *et al.* (68). These compounds form complexes with trace elements and thus prevent their precipitation. Enough ions are released through mass action to satisfy the requirements of the growing cells. Ethylenediaminetetraäcetic acid (EDTA) is the best known of the chelating agents, and Schwarzenbach & Freitag (109) have determined equilibrium constants for a number of metals and EDTA in unimetallic solution. Since many required elements may be toxic in high concentrations, chelating agents may permit the growth of an organism in a medium containing a quantity of a trace element which would otherwise be lethal.

ESSENTIAL NUTRIENTS

Carbon.—Many of the algae included among the phytoplankton have heterotrophic, chemotrophic, and autotrophic types of metabolism, and some species may exhibit all three under appropriate conditions. Fogg (35) has recently reviewed the chemotrophic assimilation of carbon. The use of organic carbon sources has been discussed by Doyle (29), Hutner & Provasoli (67), Algeus (1), Barker (11), Bristol-Roach (16, 17), Myers (84), and Pearsall & Bengry (94). Radioactive carbon has been valuable in studies of carbon assimilation and the products of photosynthesis [Calvin *et al.* (18); Gaffron *et al.* (37, 38)], and Steemann Nielsen (116) has proposed a method for determining the productivity of natural waters from the rate of assimilation of radioactive carbon. The autotrophic, or photosynthetic, assimilation of carbon will be considered here, since it is this process which makes the phytoplankton important producers of organic material in their natural habitat.

The normal requirement for carbon of various algae grown with continuous illumination and adequate nutrients varies from about 51 to 56 per cent of the ash-free dry weight (73). Spoehr & Milner (113) have shown that the carbon content of *Chlorella pyrenoidosa* may be varied from 49.5 to 70.17 per cent of the ash-free weight by modification of the medium. The highest carbon contents, associated with storage of fats, were obtained in cultures grown in continuous light, with a low concentration of fixed nitrogen, and provided with a gas mixture of 5 per cent CO_2 in nitrogen.

The quantity of carbon dioxide, bicarbonate and carbonate ions present in the water is a function of temperature, pH, excess base, and the carbon dioxide content of the gas with which the water is in equilibrium. Harvey (56) discusses the various equilibria involved and the means for computing the total carbonate and free CO_2 in sea water. The free CO_2 in the medium decreases from 100 per cent at pH 4 to virtually zero concentration at 9. The carbonate concentration increases from zero at a pH of about 7.5 to 100 per cent at pH 12. The bicarbonate is at a maximum at intermediate pH values. As a result of this complicated equilibrium, the evaluation of the utilization of the different ions has been difficult to separate from the direct effect of pH.

It has been generally accepted that the algae use free CO_2 in photosynthesis since Warburg (124) showed in 1919 that the rate of photosynthesis of *Chlorella* was dependent on the concentration of undissociated CO_2, even though both ionic forms were present in excess. Osterlind (91, 92) showed that *Scenedesmus quadricauda* can also utilize bicarbonate ions although *Chlorella pyrenoidosa* can not. Steemann Nielsen (114, 115) shows that bicarbonate ions can be utilized by other aquatic plants. Apparently carbonate ions cannot serve directly as a source of carbon in photosynthesis and Osterlind (90) indicates that an excess may inhibit growth.

It has been shown that *Chlorella* and *Hormidium* are photosynthesis-saturated at about .03 per cent carbon dioxide [Emerson & Green (30); Honert (60)] and that *Scenedesmus* is growth-saturated at this level [Osterlind (91)]. Myers, (81) has shown, however, that if the rate of carbon dioxide assimilation by the cells is high it becomes physically impossible to maintain this level without bubbling a carbon dioxide mixture through the culture. Concentrations of 1 to 5 per cent are generally used. Spoehr & Milner (113) showed that dense cultures of *Chlorella pyrenoidosa* which depended on air alone for their source of carbon produced only one tenth the weight of cells produced under otherwise similar conditions by cultures which received 5 per cent CO_2 in air. The carbon dioxide was also provided in nitrogen instead of air, at concentrations of 3, 5, and 10 per cent. The latter inhibited growth and the 3 per cent concentration limited growth with high light intensities, but gave yields equal to the 5 per cent concentration at low light intensities.

It is probably rare that the production of plant material in aquatic environments is limited by the supply of inorganic carbon since the total carbonate is generally present in great excess. The ability of some organisms to utilize the bicarbonate ion, which is at maximum concentrations at about pH 8, may be important in the success of some forms, especially in the open sea where the pH is generally uniform at about this value.

Nitrogen.—The normal requirement for nitrogen in cultures of various Chlorophyceae was found by Ketchum & Redfield (73) to be about 6.5 to 8.3 per cent of the ash-free dry weight. *Chlorella* cultures, in which the amount of growth is determined by light intensity, contain similar proportions of nitrogen in the cells [Myers (82)]. There is considerable variation, however, since cells which are deficient or which exhibit a luxury consumption of nitrogen, can be produced by changes in culture conditions (71, 73, 74, 113).

Nitrogen-deficient cells are produced if cultures are allowed to grow in the light after all of the nitrogen has been assimilated from the medium. The nitrogen content of these is about one-third (2 per cent of ash-free dry weight) of that in normal cells (71, 73). Spoehr & Milner (113) found that *Chlorella* with large fat reserves could be produced in a low nitrogen medium provided with 5 per cent CO_2 in nitrogen gas and continuous illumination at moderate intensity. Such cells contained as little as 1.17 per cent nitrogen on an ash-free basis. Nitrogen-deficient cells assimilate nitrogen from nitrate or ammonia in the dark, whereas normal cells are unable to do so without an organic carbon supply. Harvey (59) has shown that nitrogen-deficient *Nitzschia closterium* are unable to assimilate nitrite nitrogen in the dark.

A luxury consumption of nitrogen has been described by Kraus (74) who found that *Scenedesmus obliquus*, containing more than twice the normal nitrogen, were produced if growth was limited by a deficiency of the trace elements manganese, boron, and zinc.

Nitrogen-deficient *Chlorella* exhibit a complete carbohydrate metabolism for short periods, as shown by Myers & Cramer (86) and Spoehr & Milner (113) show that in older cultures nitrogen deficiency results in fat storage. The respiration rate of nitrogen-deficient cells is low [Syrett (119)] but increases as soon as ammonium sulphate is added. During the assimilation of ammonium nitrogen the respiratory quotient was unusually low (28, 119), though Cramer & Myers (28) observed high respiratory quotients when nitrate and glucose were supplied to nitrogen-deficient *Chlorella* in the dark. Syrett & Fowden (120) showed that the first products of the dark assimilation of ammonium nitrogen were principally amide and free amino acid nitrogen. Without added glucose much of the assimilated nitrogen remained in this form, but when glucose was added the assimilated nitrogen was incorporated into insoluble protein fractions. Harvey (59) also showed that the assimilation of ammonium or nitrate nitrogen by deficient *Nitzschia closterium* produced mainly nitrogen compounds soluble in hot water, and also that the chlorophyll content of the cells was greatly increased during recovery from nitrogen deficiency in the dark.

Nitrogen in the fixed form is generally available in aquatic environments as nitrate, nitrite, and ammonia. In the open ocean the concentration of nitrate nitrogen reaches a maximum of about 0.6 mg. per liter and this is about ten times as great as the maximum for the other two inorganic forms (118). Chu (19) summarizes the composition of various fresh waters and presents average nitrogen concentrations in surface waters ranging from 0.31 to 8.7 mg. per liter. As a result of growth of the phytoplankton, the fixed nitrogen in surface waters may be reduced to unmeasurable concentrations [Harvey (51); Redfield (104)]. Marine animals excrete nitrogen largely as ammonia, urea, uric acid, trimethylamine oxide and amino acids [Harvey (56)] and polluted waters may contain various organic forms of nitrogen. Cooper (26) has reviewed the forms in which compounds of nitrogen may be expected in the sea. The ability of phytoplankton to use these different forms of nitrogen directly may be of ecological importance for their survival.

Nitrogen fixation has been demonstrated for various Myxophyceae, and the evidence has been reviewed by Fogg (34, 35). There is no satisfactory evidence that algae other than Myxophyceae are capable of fixing nitrogen, though Spoehr & Milner (113) reported that the cellular nitrogen content of some of their *Chlorella pyrenoidosa* cultures was substantially more than the fixed nitrogen supplied in the medium. They do not consider their results conclusive. It is possible that other forms capable of fixing atmospheric nitrogen will be found, since very few have been investigated critically for this property.

Many investigations have shown that both ammonia and nitrate are readily available sources of nitrogen in algal cultures (28, 95, 96, 101). The availability of the ammonium and nitrate ions is related to the pH of the medium and, conversely, their assimilation changes the pH. The assimilation of ammonium ion by *Chlorella* can reduce the pH of the medium to values as low as pH 3.0, whereas assimilation of nitrate can increase the pH to 7.0 from initial values of pH 4.5 [Pratt & Fong (101)]. In growing mass cultures of *Chlorella vulgaris*, Geoghegan (39) found better yields with ammoniacal nitrogen when the pH of the medium was adjusted to 6.0 twice daily and never allowed to fall below 5.0.

The availability of these two forms of nitrogen may be different for different algae or in different culture media. Ammonium nitrogen was more rapidly assimilated than nitrate nitrogen from the same solution by cultures of the marine diatom *Nitzschia closterium* [ZoBell (126)] and by mixed phytoplankton populations [Harvey (55)]. In the latter experiments, practically all of the ammonium nitrogen was assimilated before there was any appreciable utilization of nitrate nitrogen, even though the latter was 60 times more concentrated in the enriched sea water. Ryther (107) found, however, that *Nitzschia closterium* was unable to grow with ammonium nitrogen, though *Nannochloris* and *Stichococcus* grew more rapidly on ammonium than on nitrate nitrogen.

Nitrite is present in natural waters at low concentrations and is an available source of nitrogen. Ludwig (76) found it toxic to *Chlorella* in higher concentrations, and ZoBell (126) found it less toxic than ammonium but more toxic than nitrate nitrogen in his sea water cultures of *Nitzschia closterium.*

The availability of other forms of nitrogen has also been investigated. Ludwig (76) studied the ability of *Chlorella* to use many forms of nitrogen, and his bibliography of over a hundred references is an excellent review of earlier work. Acetamide, urea, guanidine carbonate, uric acid, several amino acids, and peptone were suitable sources of nitrogen. Schreiber (108) found that bacteria-free cultures of *Carteria*, a marine flagellate, can utilize glycine, and Braarud & Føyn (15) found that *Chlamydomonas* can utilize glycine, alanine, and asparagine. Algeus (1, 2, 3, 4) has investigated various organic nitrogenous compounds in the nutrition of several Chlorophyceae. In some the rate of nitrogen assimilation was limited by deamination; in others, with more rapid deamination, ammonia was excreted into the medium.

The optimum concentration of the nitrogen supply is apparently very different for different species. *Chlorella* is very tolerant of variations in nutrient concentrations, and Myers (83) found that the major salts could be varied by dilution of the entire medium twenty-fold without influencing growth or photosynthetic behavior. The composition of his undiluted medium is given in Table I and contains 168 mg. of nitrogen per liter. Ammonium nitrogen concentrations greater than 31.5 mg. per liter were found by Spoehr & Milner (113) to inhibit the growth of *Chlorella pyrenoidosa*, though Geoghegan (39) found that *Chorella vulgaris* grew well at much higher ammonium nitrogen concentrations provided the pH of the medium was controlled.

The marine diatom *Nitzschia closterium* also appears to grow well regardless of variation in nitrogen concentration. The rate of growth of cultures of *Nitzschia closterium* was independent of the nitrate nitrogen concentrations between 0.05 and 0.5 mg. per liter [Ketchum (70)], though the rate of assimilation of nitrogen was decreased when the medium contained less than 0.2 mg. per liter. Under different culture conditions Ketchum & Redfield (72) obtained about the same rate of growth with this marine diatom in a medium which contained 15 mg. N per liter. ZoBell (126) found that the upper limits of concentration for optimum growth of *Nitzschia closterium* in ammonium, nitrite, and nitrate-nitrogen media were respectively 0.7, 70, and 560 mg. N per liter.

Chu (20) found, however, that the rate of growth of various species was limited by concentrations greater than 5 to 17 mg. N per liter as shown in Table II. These concentrations are much less than those commonly used in culture media for *Chlorella* (cf. Table I), but are greater than those normally found in nature. Little difference was found between ammonium and nitrate nitrogen in Chu's experiments. Rodhe (106) found that the initial rate of growth of *Ankistrodesmus falcatus* was equal for nitrogen concentrations from

0.15 to 10.0 mg. N per liter whether the nitrogen was supplied as ammonium chloride or calcium nitrate. After longer times, however, growth was limited in the lower concentrations presumably because of the complete removal of nitrogen from the medium. The growth rate also decreased in the higher ammoniacal nitrogen concentrations, being less in the 10 than in the 5 mg. N per liter after six or more days. He attributes this inhibitory effect to the rapid assimilation of CO_2 by highly productive cultures with resultant pH values of 11 or higher, thus liberating free ammonium hydroxide in the culture.

Dinoflagellates can utilize very low concentrations of nitrogen, and Barker (10) found that growth rate was not limited unless the sodium nitrate enrichment was less than 0.001 mg. per liter. Additions of more than 0.01 mg. ammonium chloride per liter inhibited growth of *Prorocentrum micans* and a *Peridinium*. Gerloff, Fitzgerald & Skoog (41) found that the yield of cultures of the blue-green alga *Coccochloris peniocystis* increased with increasing nitrate content of the medium up to a concentration of 13.6 mg. N per liter.

TABLE II

Maximum Concentrations (Mg. N per Liter) of Nitrogen for Optimum Growth of Various Algae. [After Chu (20)]

Species	$NO_3^- - N$	$NH_4^+ - N$
Pediastrum boryanum	10.4	10.6
Staurastrum paradoxum	8.5	5.3
Botryococcus Braunii	6.9	
Fragillaria crotonensis		13.1
Nitzschia palea		6.5
Asterionella gracillima	17.1	

It appears, therefore, that *Chlorella* and *Nitzschia* are relatively insensitive to variations in the nitrogen content of the medium (provided it is present in excess) but that some species of algae can be inhibited in rate of growth by excessive nitrogen concentrations. Additional studies would be desirable especially concerning the effect of pH on optimum nitrogen concentrations. These should be conducted under continuous flow or diffusion conditions to avoid exhaustion of the nutrient medium (85, 106).

Phosphorus.—The normal phosphorus requirement of various Chlorophyceae is about 2 to 3 per cent of the dry weight of cells (73). This a greater proportion than Redfield (104) found for natural collections, though marine diatoms, having heavy siliceous shells would be expected to contain somewhat less phosphorus on the dry weight basis (33, 73). The phosphorus content can also be varied greatly by rearing cultures in deficient media

(71, 73), and luxury consumption with storage of excess phosphorus has been observed by Lund (77), Goldberg *et al.* (43), and Rodhe (106).

Phosphorus-deficient cells can be produced by permitting cultures to grow and reproduce after complete removal of all of the phosphate from the medium. Franzew (36) produced deficient *Scenedesmus quadricauda* and *Pandorina morum* in this way which contained as little as one-ninth the normal phosphorus content. Deficient cells of *Nitzschia closterium* and *Chlorella pyrenoidosa* were produced in the same way by Ketchum (71) who showed that such cells were capable of assimilating phosphate from the medium in the dark to satisfy the phosphorus debt thus incurred, though cells grown in a complete medium did not assimilate phosphate in the dark. Phosphorus-deficient *Chlorella pyrenoidosa* assimilates potassium as well as phosphorus in the dark, the two elements being absorbed in approximately equivalent amounts on a molar basis [Scott, (112)]. Calcium and magnesium were not assimilated under these conditions.

Rodhe (106) indicates that, in addition to satisfying the phosphate debt by assimilation in the dark, *Scenedesmus quadricauda* can store excess phosphorus provided adequate supplies are available. Such cells, when returned to the light in a phosphorus-free medium were able to grow as rapidly as those in an adequate medium. The assimilation to satisfy the phosphate debt proceeded very rapidly (one day), but the accumulation of extra phosphorus required a fairly long time (7 days).

The content of phosphorus in the cells can be expected to be variable, especially when grown in media containing low concentrations of phosphate. It was shown, for example, by Ketchum (70) that the rate of assimilation of phosphorus by *Nitzschia closterium* was directly related to the phosphorus concentration below about 0.1 mg. P per liter and also to the concentration of nitrate nitrogen below 0.2 mg. N per liter. In these experiments phosphorus concentrations less than 0.017 mg. P per liter limited cell division as well as the rate of assimilation. Lund (77) has shown that *Asterionella formosa* is variable in the amount of phosphorus contained per cell, and he attributes the difference to storage of excess phosphorus by cells grown in phosphate-rich media.

Goldberg, *et al.* (43) using radioactive phosphorus found a linear relationship between the phosphorus content of the diatom *Asterionella japonica* during exponential growth and that of the medium within the range .015 to .110 mg. P per liter. The range of variation within the cells was, however, only about one-half of the range in the medium. As much as 50 per cent of the radioactive phosphorus in cells containing more than the minimum requirement could be removed by washing with sea water free of radioactive phosphorus [Goldberg *et al.* (43)]. The minimal amount of phosphorus was found to be strongly bound, since little regeneration in the medium was observed after three weeks storage in the dark, although the cultures were not bacteria free.

The physiological state of the cells may also be important in determining their phosphorus content. Old dense cultures of *Stichococcus bacillaris* were found by Ketchum & Redfield (73) to have high phosphorus content, though *Chlorella pyrenoidosa* showed no progressive change of phosphorus content with age of the culture.

Without analysis of the cells, or experiments to determine whether phosphorus assimilation can proceed in the dark, it is impossible to differentiate between excess storage, normal content, and deficient cells.

Ortho-phosphate is the form normally found in natural waters and used in culture media. Chu (22) reports that pyro-phosphate cannot be used by *Phaeocystis pouchetti*, *Skeletonema costatum*, and *Nitzschia closterium* as effectively as the ortho-phosphate. Bacteria-free cultures of *Nitzschia closterium* can utilize inositol hexaphosphate and glycerophosphate when growing in the light [Chu (21)], and Harvey (58) showed that phosphorus-deficient cells can also assimilate these compounds in the dark.

The optimum phosphorus concentrations for growth of the various species listed in Table II was studied by Chu (20). The upper limit which permitted maximum growth rates varied from 8.9 to 17.8 mg. P per liter, higher concentrations being inhibitory. Gerloff, Fitzgerald & Skoog (41) obtained maximum rates of growth with the blue-green *Coccochloris peniocystis* at phosphorus concentrations of 0.45 mg. P per liter. Their highest concentration tested contained 5.4 mg. P per liter and was not inhibitory. Rodhe (106) found very different optimum requirements for various species. *Ankistrodesmus falcatus* reproduced at the same rate for the first three days in cultures containing 0.005 to 1.0 mg. P per liter. With increasing length of time the growth rate decreased in progressively higher concentrations so that after eight days maximum growth was found only in the highest concentration. For the lower concentrations (<0.2 mg. per liter) the number of cells produced after 15 days was directly proportional to the concentration of phosphorus in the medium, indicating that the minimum phosphorus requirement was limiting growth. In higher concentrations the direct relationship was not found and Rodhe concluded that, in these cultures, the nitrogen supply was limiting. The growth of *Scenedesmus quadricauda* also increased as the phosphorus concentration increased up to 1.0 mg. per liter, but additions of only 0.002 mg. P per liter to Lake Erken water gave maximum growth of *Asterionella formosa* and addition of 0.05 or more mg. per liter inhibited growth of this form. Preliminary observations indicated that additions to Lake Erken water of 0.005 or more mg. P per liter was sufficient to inhibit growth of *Dinobryon* and *Uroglena*. It is of interest that *Dinobryon* blooms occur in lakes after a decline of other species. Pearsall (93) correlated these blooms partly with nitrogen:phosphorus ratios, a high ratio being favorable. Chu (22) however, concludes that this ratio is unimportant while each element remains within the optimum range of concentrations. Hutchinson (69) found evidence that *Dinobryon* can increase at lower nutrient concentrations than antecedent species which might be diatoms, *Scenedesmus* or blue-green algae. The inhibition of growth by relatively low concentrations of phosphorus may be the explanation for the failure of *Dinobryon* to bloom except following growth and the resultant assimilation of nutrients by other species.

Sulfur.—Kraus (74) reports a sulfur content of *Scenedesmus obliquus* of 0.91 per cent of the total dry weight. Sulfur is an invariable constituent of living matter, and is generally provided as sulfate in culture media. However, no studies on the effects of varying concentrations of sulfate on the growth of alage have been found. Harvey (56) reports that the normal sulfate content of sea water suffices for the growth of a number of planktonic diatoms.

Harvey (54) found that the marine diatom *Ditylum* was unable to grow normally in some samples of sea water collected during summer months unless a compound containing divalent sulfur was added. Sodium sulfide or the organic compounds cystine, glutathione, methionine, and thiamin were found to restore the fertility of the water. Matudaira (79) found that additions of 0.1 to 1.0 mg. per liter of $Na_2S \cdot 9H_2O$ stimulated the growth of *Skeletonema costatum* in sea water, but that 5 mg. per liter arrested cell division and no cell division occurred when 10 mg. per liter was added. Cystine and alanine were also effective. Auxospore formation was promoted by the addition of sulfides. Since he was unable to grow this diatom in artificial sea water, with or without added sulfide, he concluded some unknown accessory was also needed.

Calcium and magnesium.—These two elements are discussed together because studies have generally been made by substituting a salt of one for the other in the culture medium.

It has frequently been shown that calcium is not essential for the growth of *Chlorella* (63, 81, 110, 123) and many culture media (cf. Table I) omit calcium. Rodhe (106) found no effect on growth of *Ankistrodesmus falcatus* as a result of varying the calcium content from 1 to 10 mg. calcium per liter, and Trelease & Selsam (123) found no effect on growth of *Chlorella* by additions up to 160 mg. per liter. Gerloff, *et al.* (41) found calcium unnecessary for the growth of the blue-green *Coccochloris peniocystis.* Manuel (78) and Noack: *et al.* (88) found, however, a need for calcium by *Chlorella*, and Hutner (66) has found a calcium requirement of 5 mg. per liter for the marine diatom *Nitzschia closterium.* Chu (22) indicates that the minimum value of calcium for good growth depends upon the medium used and upon the species of algae. It is possible that some of his results reflect a pH effect which is not recorded.

The absolute requirement for magnesium is well established. The addition of as little as 0.1 mg. per liter produced optimum growth of *Ankistrodesmus falcatus*, and no inhibition of growth was found up to 10 mg. per liter [Rodhe (106)]. Different optimum concentrations for various species and for different media were reported by Chu (22). The minimum concentration which produced good growth in his medium 9 was 0.01 mg. per liter for diatoms, though 4.0 mg. per liter was required by *Staurastrum paradoxum.* Concentrations which inhibited growth in this medium ranged from 48 mg. per liter for diatoms to 1 mg. per liter for *Pediastrum boryanum.* Trelease & Selsam (123) found that the concentration had to exceed 480 mg. per liter to inhibit growth of *Chlorella.* Some of the discrepancies may not be due to different species or media, since Finkle & Appleman (32) have shown that concentrations less than 2.8 mg. per liter reduced the division rate of *Chlorella,* but not the rate of production of dry weight.

Hutner (66) has used a "citrate extinction" technique to determine both the calcium and magnesium requirement of the marine diatom, *Nitzschia closterium* in a completely artificial medium. The method depends upon the determination of magnesium or calcium requirement at various citrate concentrations and extrapolation of the results to zero citrate where the total concentration would be present in the ionic form. The minimum concentrations obtained in this way were about 5 mg. Ca, and 40 mg. Mg per liter.

The calcium and magnesium content of *Chlorella pyrenoidosa* when grown in media containing various proportions of these two elements has been determined by Scott (110). No inhibition of growth was found when calcium was omitted, and the cells produced contained no calcium, indicating that no appreciable supply was available as a contaminant. The ratio of calcium to magnesium in the cells gave a linear relationship with the ratio in the medium, though a three-fold variation in the medium produced only a 1.4 fold variation within the cells. In these experiments the calcium content, on an ash-free dry weight basis, varied from 0 to 0.58 per cent and the magnesium content varied from 0.29 to 1.37 per cent. Scott (111) further found that the calcium content was replaced to a large extent by magnesium and partially replaced by sodium or potassium when the cells were washed in distilled water solutions of the chlorides of these ions. Part of the magnesium, however, was firmly bound and this quantity was greater than the magnesium present in the chlorophyll.

Sodium and potassium.—There is no evidence for a requirement of sodium for algae. Pratt (100) has observed an effect of the sodium:potassium balance on photosynthesis of *Chlorella* in bicarbonate buffers, and Emerson & Lewis (31) have reported a high sodium, low potassium requirement for *Chroococcus.* Media containing no sodium, however, permit an abundant growth of a large variety of algae.

The effects of potassium have been extensively studied by Pirson (97, 98) and Pirson & Wilhelmi (99). Potassium-deficient cells show a low rate of growth and photosynthesis, and a high rate of respiration. Rapid restoration to normal was observed following the addition of potassium or rubidium, but lithium, sodium, and cesium were not effective. Scott (110) found the growth of *Chlorella pyrenoidosa* was depressed with less than 7.8 mg. K per liter in the medium and both the potassium and phosphorus content of these cells was less than normal. Increasing the potassium to double this concentration, however, resulted in no further uptake of this ion and these cells contained about one per cent potassium. At low concentrations of potassium, the sodium content of the cells was considerably increased, but at higher concentrations it remained constant at about 10 per cent of the potassium in the cells. Provided sufficient potassium was available, the ratio of potassium to sodium within the cell was independent of the ratio in the medium. The potassium was firmly bound within the cells and could not be removed by washing them with distilled water solutions of sodium, potassium, or magnesium chlorides [Scott (111)].

Iron.—The requirement for iron for the growth of algae is well substantiated (61 to 65; 84, 106), though the way in which the iron should be provided has been a subject of controversy. The solubility of iron in alkaline solutions is very low and Cooper (25) concluded that less than 10^{-7} mg. per liter of ionic iron can exist in the sea in equilibrium with ferric hydroxide. Harvey (53) concluded that the phytoplankton of the sea can utilize iron in colloidal suspension.

Goldberg (42) using radioactive iron, found that the marine diatom *Asterionella japonica* utilized only particulate or colloidal iron for growth whereas iron present as a complex of citrate or a synthetic humic acid was not available. He concluded that a direct study of particulate iron and its size distribution is necessary in determining the nutrient availability of the iron. In culture media iron is frequently supplied in an inorganic form, most of which must be present as colloidal particles in alkaline solutions. Myers (84) and Gerloff, Fitzgerald & Skoog (41) show that aged nutrient media containing inorganic iron are less effective than media freshly prepared. This change must indicate the aggregation of colloidal particles.

It was suggested by Gran (44) that the early growth of phytoplankton populations in inshore water and over banks might be due to the presence of high iron concentrations washed out with humus compounds from the soil. It is possible that some of the success of soil extract in obtaining cultures can be attributed to the ability of humic acids to maintain the iron in an available form [Pringsheim (102)].

The use of iron as the citrate complex was suggested by Hopkins & Wann (64), and Rodhe (106) discusses the change in availability of iron in this form as a result of aging, autoclaving, and light. The citrate complex was found to be more effective as a source of iron in low concentrations than ferric chloride but both were equally effective in higher concentrations [Gerloff *et al.* (41)]. The growth of *Ankistrodesmus falcatus* was negligible when no iron was added [Rodhe (106)], but 0.04 mg. Fe per liter was sufficient to give maximum growth. Above concentrations of 2 mg. Fe per liter inhibition of growth was observed. Myers (83) found that concentrations of iron ranging from 0.01 to 7.4 mg. per liter gave adequate growth of *Chlorella*, but in continuous flow cultures a concentration of 0.5 mg. per liter limited growth while concentrations above 5.0 mg. per liter were adequate (85).

Silicon.—The growth of diatoms rapidly removes silicates from the surface waters of the sea [Atkins (7, 8); Cooper (24); Hart (49, 50)]. The direct relationship between silicate concentration and diatom growth needs further investigation, though Harvey (52) has shown that addition of silicates to sea water may stimulate growth of *Nitzschia closterium*, and Chu (19) has investigated its requirement by various fresh water diatoms. Harder & Witsch (48) obtained increased yields of moss cultures of diatoms by the addition of sodium "wosserglas" up to 0.16 per cent, though 0.3 per cent produced an inhibition. Precise experiments are needed, however, in which all contact with glass containers is eliminated.

Hart (49, 50) and Clowes (23) believe that low silicate concentrations limit the rate of diatom growth in the antarctic during the summer when unusually thin-walled diatoms were observed. Atkins (9) has compared the changes in silicate and in phosphate content of the waters of the English Channel, and concluded that the large proportion of phosphorus removed indicates that forms other than diatoms must account for a large part of the organic matter production.

Manganese.—Variable and small quantities of manganese have been found in the surface waters of the Pacific by Thompson & Wilson (122). Harvey (54, 57) has shown that the addition of one part of Mn per thousand million parts of sea water is sufficient to produce vigorous growth of *Ditylum brightwelli*, a *Chlamydomonad*, a marine *Chlorella*, a *Cryptomonad*, and two *Chrysomonads*. The addition of manganese to deficient *Chlorella* cells was shown by Pirson (97) to cause an immediate increase in photosynthesis, though Harvey (57) shows a prolonged lag period before the start of active growth of the marine *Chlorella*.

Manganese is important in nitrogen metabolism, and Kylin (75) shows that it stimulated growth of sporelings of *Ulva lactuca* when nitrate, but not when ammonium nitrogen was supplied. Harvey (57) and Noack & Pirson (87) found stimulation with both forms of nitrogen.

Trace elements.—Trace element solutions, such as Arnon's (6), are commonly added to supply possible additional needs of algae. A requirement for traces of zinc has been shown by Ondratschek (89) for various flagellates and by Stegmann (117) for *Chlorella*. Copper may be required [Gusserva (46, 47)] but Greenfield (45) has shown that it inhibits photosynthesis at very low concentrations (10^{-7} M). Provasoli & Pintner (103) have shown that traces of Zn, Mn, Cu and Co are required by several algal flagellates. Gallium was found by Riley (105) to stimulate cell production in cultures deficient in phosphorus and nitrogen, but had no effect if these nutrients were also added. A requirement for molybdenum has been demonstrated for some nitrogen-fixing, blue-green algae [Fogg (35); Bortels (13, 14)].

The establishment of requirements for trace elements demands rigorous purification of all of the ingredients of the culture medium. As suggested by Hutner *et al.* (68) further improvements in techniques are likely to establish additional requirements which are now unknown because the nutrients are added in adequate supply as contaminants with the various chemicals or water used. The potential value of complexing agents, such as ethylenediaminetetraacetic acid, in establishing requirements for trace elements is stressed by Hutner *et al.* (68) and by Provasoli & Pintner (103).

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Contribution No. 689

MEASUREMENTS OF THE OCEANIC CIRCULATION IN TEMPERATE AND TROPICAL LATITUDES*

William S. von Arx

OCEANIC CIRCULATION

At the present time the circulation of the oceans in temperate and tropical latitudes presents at least two rather separate aspects for study; the wind-driven system extending perhaps to the depth of the main thermocline, and a deep circulation system in which secondary effects of the wind-driven system and thermohaline effects may both be significant.

The wind-driven system has received the bulk of recent observational and theoretical study. In this work observers are equipped to make only fragmentary measurements of transient occurrences, while theoretical effort has been concerned mainly with the steady state, wind-driven circulation. It is difficult to reconcile these two kinds of results. Midway between them is the transient state which both groups hope to describe sooner or later.

Since physical intuition is acknowledged as an unsafe basis for the theoretical description of the oceans, it is necessary at first to describe transient conditions from observations. This description must be based mainly on direct observations taken simultaneously over a sufficiently large area to have synoptic meaning, and for a long enough time to distinguish the longer periodic variations from secular trends. It should be acceptable, at first, to average out the smaller scale turbulent processes so that only the bolder features of the flow pattern are revealed. Even so, this is a more ambitious program of observations than can be managed at present.

It seems evident that rather than new instruments we require new methods of observation which are adapted to the scale of the field problem. These methods should possess elements of speed and penetration to depths which far surpass those attainable from moving ships or aircraft for we would like to observe what is happening simultaneously at many places in the ocean and continue such observations for some time. Fixed ocean stations might be desirable. These might be designed either to record events against time, or report them at intervals.

In that the fine structure of the ocean's cannot be inferred by interpolation, it also seems desirable to increase the density and simultaneity of observations from ships. This might be done by providing measuring devices which drift with the water to establish the continuity of the ocean structures between successive traverses by ships. These devices may also link observations from aircraft to the occurrences in the upper layers of the ocean.

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In order to decide what is to be required of these instruments and how they may be designed, it seems necessary to review present ideas concerning some of the phenomena of oceanic circulation to see what may be observed.

THE STEADY AND TRANSIENT STATES OF OCEANIC CIRCULATION

Stommel (1948) and Munk (1950) have offered a very satisfying theoretical description of a primary oceanic circulation system driven entirely by the mean zonal wind stress. Recently it has been possible to simulate qualitatively not only the graphical results of this mathematical model, but a number of secondary details of the ocean prototype in a rotating model (von Arx, 1952a). In these experiments a pattern of motion similar to the surface circulation of the ocean prototype has been produced in homogeneous water. The circulation develops almost immediately after a steady wind torque is applied, and coasts to a stop nearly as rapidly when the wind torque is removed. This result appears to support the growing impression that the superficial motions respond to a seasonal change in wind torque with little delay (Fuglister, 1951), but that large scale adjustments of the density structure take place much more slowly. The adjustments of the density structure may be effected by two mechanisms, or possibly three, having different times of response and different areas of influence. Since the Gulf Stream has been studied in some detail by many investigators, it serves especially well as a focus for discussion of these effects.

Seasonal variations in the transport of the Gulf Stream (Iselin, 1940) have been observed by the method of dynamic sections and are indicated to some extent in tide gauge records. Yet, in different authors' opinions, theoretical estimates of the rate of response of the density structure to a change in wind stress range from less than a decade to a millenium. In any case, it is longer than a season. Since the sun may not supply heat rapidly enough to change the volume of specifically light water in the Sargasso Sea by the amounts required to compensate the seasonal rate of change of wind stress, the compensating pressure gradients may be derived from a temporary deformation of the Sargasso water mass. Iselin has suggested (1940) that in periods of greater than average wind stress the horizontal extent of the Sargasso Sea may diminish in order that the pressure gradients may be temporarily increased through elevation of the free surface and depression of the main thermocline. These effects are thought to be reversed in the event of less than average wind stress. This response of the density structure would tend to distort the circulation pattern and cause it not to fit exactly within the geometry of the ocean basin. To compensate for this a change in volume of the Sargasso water mass is required which will take place at a secular rate determined by the ability of the sun to heat the added volume or by the ability of dissipative effects to cool enough water to restore the circulation to its normal geographic course. Were the rate of change of wind stress slow enough for the secular rate of accumulation or dispersal of specifically light water to keep in step, the volume of the Sargasso water might change while its horizontal extent remained constant.

While the elastic deformation of the whole Sargasso water mass may be rapid in comparison with the rate of accumulation or dissipation of specifically light water, there may be localized deformations of the pressure field that occur still more quickly; perhaps as rapidly as the response of the superficial circulation to a change in wind stress. A sudden increase in the velocity of the Gulf Stream would be accomplished by a corresponding increase in the Coriolis force. This would cause the motion to be directed to the right of the isobars and for water to be pumped toward the right side of the current and away from the left. In this manner a topographic trough may develop on the left and a ridge on the right of the current which would locally steepen the pressure gradient across the Gulf Stream and give rise to temporary countercurrents. There is evidence of such effects but it is too early to be certain of this interpretation.

While these effects may help to maintain a constant pattern of circulation under a wind pattern of variable intensity, there are anomalies in both the wind pattern and the flow pattern. In the equilibrium state it is considered that the climatological mean wind torque supplies the energy needed to overcome the frictional losses accompanying geostrophic motion across the pressure gradients. Frictional losses are thought to be greatest by far in the region of westward intensification of the current systems. Since the wind torque is accumulated over the whole ocean surface, the braking action in the zone of westward intensification must be very intense. Braking seems to occur not only as a result of water shearing over itself or against the continental boundaries, but by meandering and the shedding of eddies. The meander patterns in the westward intensified flow are well recognized (Iselin and Fuglister, 1948) (Fuglister and Worthington, 1951). The centrifugal accelerations accompanying meander curvature may sometimes amount to more than 15 per cent of the local pressure gradient acceleration (von Arx, 1952).

There may be other accelerations associated with the displacement meanders or their form drag as they move along the length of the current. Since the water masses on the right and left of the current are of different character, a meander represents a pair of waves moving in phase along both the right and left-hand density interfaces. The left interface separates the water masses having the greatest difference in density, so that waves on this interface, described theoretically by Haurwitz and Panofsky (1950), may dominate the wave pattern and motion. In order for a meander to grow or to progress it is necessary for the wave forms on both interfaces to remain approximately in phase and for the water masses adjoining the current to move about harmoniously as the waves pass. Through a combination of vertical and horizontal motions the water mass on the convex side of the current must withdraw, and that on the concave side must advance as a meander deepens. At the same time the reverse must occur as the meander progresses. This may give rise to characteristic circulation patterns in the adjacent water masses. It seems unlikely that with an inequality in the density differences on either side of the current the rate of progress of the waves along the borders of the adjacent water masses can be so harmonious that there will be no change in either the pressure difference across the current or of the width and depth of the current. Localized convergence and divergence of flow and accelerations of other kinds may influence the details of motion even if the system is broadly in geostrophic equilibrium. That is to say, the equilibrium state is not necessarily a steady one.

Finally, currents like the Gulf Stream are not driven primarily by local winds. The passage of storm centers across these currents and neighboring water masses may influence the results of direct current measurements near the surface and cause temporary departures from geostrophic motion, probably involving cyclic motion in inertia circles. These add many difficulties to the problem of relating field observations to the broad ideas that have been discussed, and suggest both the length of time observations must be carried on to obtain a fair sample and the detail that would be desirable in describing the transient state.

As a step to broaden the scope of observations, the tendency recently has been to measure the properties of the surface layer from ships moving at cruising speed. This present trend to rapid surveys with one or more ships is not likely to bear fruit of the necessary quality or quantity for study of the volume circulation unless ships can be made to sail faster and instruments can be devised for working at all depths at these higher speeds. According to present views, increased ship speeds exclude the possibility of apparatus being towed very much deeper than the 100 meter level.

ANCHORED BUOYS AS OCEAN STATIONS

One direction instrumentation may take is in the development of anchored apparatus designed to measure at many depths at least the scalar quantities now used to describe the ocean water masses and their motions. An extended pattern of such stations outfitted to measure the ordinary scalars at several depths, on a schedule consistent with their spacing, would do much to indicate how steady or unsteady is the distribution of these properties of the ocean and the motions associated with them. The stations might be distributed in such a way that approximately equal volumes of water would pass between them. Were it convenient to measure the velocity of water passing these stations at several depths, the departures from geostrophic equilibrium might be detected as well as readjustments of the pressure pattern.

The stations might be equipped either to record or telemeter observations, or both. At first they might only make measurements of the temperature at a number of levels, and of the pressure at a few levels. This simple combination would permit studies of the fluctuation of the level of the thermocline and to some extent, the shifting boundaries of water masses having sufficient temperature contrast. Pressure indicators would indicate how much the wire is inclined, and this would suggest the presence of strong currents, supply information on their thickness and indicate the changing pattern of meanders. A light intensity meter in the surface float might serve the dual purpose of marking the lapse of days and estimating the cloudiness. It would also indicate the periods when the surface float had been towed under. Later on, some means for measuring salinity or density in situ would be desirable. Since these quantities are approximately known or can be found at each predetermined level, differential methods might be devised which use an enclosed water sample from that depth as a standard.

It is easier in several respects to develop or adapt existing instruments for such stations than to provide good ideas for a solution of the permanent anchoring problem. Stommel has calculated that a vertical steel wire of any diameter will not support its own weight with a safety factor of 2 if it is more than 30,000 feet long. Therefore, tapered wire seems desirable if steel is used. There is also the possibility of using materials other than steel which have sufficiently low density for buoyant forces to be important. The properties of a number of materials such as glass, various plastics, and non-ferrous metals have been reviewed. As yet no substance has been found free of certain disadvantages but the buoyant cable principle offers promise. If measurements are to be made at many levels the cable must contain electrical conductors although these need not be very heavy gauge. Various types of anchors have been considered. An ordinary coring tube driven into the bottom seems to have many good properties, and if the chain permitting the final free fall were quite long it would have a desirable shock-absorbing effect against sudden strains transmitted along the cable.

There is also a choice to be made as to whether the float at the upper end of the cable should ride on the surface or be held at a certain depth below it. A float at the surface would be subjected to violent wave action at certain times while a submerged float would be more protected. However, the stretching of cables several miles long may be considerable, and even if a float were initially below the surface, elastic extension and subsequent slow creep might allow it to reach the surface with effectively no scope. Either surfaced or submerged, buoys must be designed to withstand considerable hydrostatic pressure since they are liable to be towed under when they happen to lie in the paths of strong currents. It seems likely that buoys might be towed under to depths as great as 55 meters in the Gulf Stream, so that they must be designed to survive exposure to more than the pressure at this depth, even though they are to be primarily surface or near-surface floats.

There are advantages in placing buoys in the region of strong wave action since they may be recovered more easily and in this position they might provide information on the intensity of wave action or use it as a source of power. For example, a pendulum arranged to wind a spring could drive a generator as a trickle charger for storage batteries. It is interesting to note that storage batteries preclude the use of sealed floats due to the hydrogen they generate. A check valve of some kind will be required to prevent explosions.

Finally, there are the problems of telemetering or recording the data obtained at the stations and servicing the buoys. If the surface buoys are located far enough apart, the time of sunrise and sunset will schedule transmissions mainly according to longitude. Should a buoy break loose this fact will be known by the unusual transmissions schedule and the inconsistent nature of the data transmitted. If the buoy is not heard from for a few days it may have been towed under temporarily, but if it is not heard from for some longer time, it must be either sunk or in need of repair. Under these circumstances a service vessel is to be dispatched.

The service vessel will be faced with a difficult problem in navigation; to find an object nearly awash and possibly no more than 5 or 10 feet in diameter at anchor in 2 or 3 miles of water on a scope of perhaps 1.5 to 1. Sonar may help, but a radio homing transponder might shorten an otherwise lengthy search if the buoy has sunk. Since a service vessel may be needed quite often, it will have opportunities to contribute numbers of observations gathered en route.

Protest might be raised against ocean buoys as a menace to navigation. As a safety measure the buoys, though able to withstand fairly high hydrostatic pressure, should be brittle and break apart on impact. Glass and some plastics have this combination of properties. Similarly, the cable anchoring them to the bottom should be strong in tension but weak in shear, as are glass and some plastic fibers, so that the diving planes and screws of submarines may not be fouled. Plans have been considered in which a submerged float, to lift the burden of the cable's weight, lies below wave action, while a smaller float on the surface may house a radio transmitter and support the antenna. Buoys for this arrangement might be made to resist impact since the smaller float would have little inertia and its cable be small, while the deeper float and stronger cable might be placed below the range of submarine navigation.

From a more positive point of view, an extensive grid of anchored buoys, if listed on charts, might serve as position markers in the otherwise trackless ocean. If buoys were to be equipped with a suitable button marked "DISTRESS CALL" they might be activated to that purpose and serve as a mooring for lifeboats until help arrived. Such a service built into ocean buoys might cause them to be respected by mariners.

There has been some thought given to the choice of recording or telemetering data from ocean stations. It seems best that both be done. A telemetering installation will reveal whether or not the station is operating satisfactorily as well as provide a running account of the occurrences at its position. Such information would help in planning cruises as well as improve their effectivness while in progress. But since buoys may not always remain on the surface or transmitters may fail, the telemeter link may be broken from time to time. Records made within the buoy would help to fill the gaps in the telemetered record and provide a running check on the accuracy or origin of the information received by radio.

Recording apparatus for observations over an extended time is in process of development. Stommel and Frantz are considering designs for a recording buoy which will sink to the bottom and record the pressure. If the bottom pressure fluctuates tidally and level isobaric surfaces lie above the bottom, something may be learned of the ocean tides and the pressure fields associated with the deep circulation from such bottom mounted instruments. If the pressure fields associated with the motions above the thermocline are not in geostrophic equilibrium, the secular change in these may be recorded as well. Stommel has considered the problem of recovering these objects and believes that if a sufficient length of submarine cable is attached to each instrument, it should be possible to grapple for the cable, following the successful precedents of commercial cable companies. The results of recent experiments in shoal water are encouraging.

Other unattended recording instruments are actually in existence; namely the recording thermograph and the recording current meter designed by Klebba. These instruments cannot be set out at great depths as they are built at present, but they will record events for 400 days.

DRIFTING BUOYS

In connection with present observational techniques, one of the most pressing interpretative problems is that of joining with pencil lines the scalar and vector observations made on successive traverses by one or more ships. Contours may be drawn through a field of scalars in several equally acceptable ways. Choices are more limited for a vector field and no choice can be justified without reference to at least a few representative streamlines or particle trajectories. There are also purely navigational difficulties of knowing where each observation was made in the geographic framework and since it takes time for ships to move about through the changing fluid structure, purely geographic considerations may not suffice. Usually we have no assurance that the changes in the fluid system are slow enough to be neglected in connecting the observations made at different times. The results of the multiple ship survey of the Gulf Stream in 1950 suggest that data from six ships could be safely collected for each day and treated as though they had all been taken simultaneously. The element of convenience doubtless weighed heavily in coming to this conclusion. From this, one is led to think that had it been posible to have not only moving ships in the field but drifting ships as well, the paths of motion and observations made by the ships drifting with the flow would have been useful guides in connecting observed points between the traverses made by the ships moving across the grain of the fluid structure.

Rather than drifting ships, it is, of course, more economical to use drifting buoys equipped to detect the local temperature and position and either to record these against time or telemeter the data to the ships or to shore. The streamlines described by drift of the buoys suggest a proper mode of interpolation between observations made on adjacent traverses by nearby ships. As each wave of buoys drifts through the same area, changes in the pattern of motions may be revealed. This kind of evidence is essential to a description of the fine structure of the transient state. In addition to evidence of the change in the strength of currents, horizontal confluence and difluence of surface flow, there may be a measurable change in the properties of the water parcel near each buoy as it moves through the area.

The drift of the buoys would only suggest the nature of the mean streamflow, for each buoy would tend to move in a random way with respect to the mean motion vector. Since the mechanism of eddy diffusion, particularly on a large scale, is not well understood, this might be studied separately by releasing a group of buoys at one point for the purpose of observing their scatter and the changes in water properties detected within the buoy field. It is also possible that in some regions where the current pattern is not immediately evident, the mean motion vector is small compared with the random component. Were the mean motion vector subtracted and the currents plotted, in effect, with respect to a reference frame moving at the mean motion rate, some intelligible systematic motions might appear.

In view of these possible uses for surface buoys and their apparent promise of new and desirable kinds of data not easily obtained from shipboard, some thought has also been given their use in obtaining subsurface data and the modifications of design that may be required.

Buoys which telemeter their position may be used, for example, to indicate currents and trends of motion at depths below the surface if they are equipped with large current crosses or other suitable drags to dominate their motions. With such equipment already below the surface it would be a relatively simple matter to suspend the drag on an electric cable and measure temperature or other scalars at that or lesser depths. It is also possible to suspend one or more current meters below an otherwise undamped surface buoy to measure the vertical shear. With the development of suitable inclinometers, a current cross might be used to measure vertical shear adapting the technique of Pritchard and Burt (1951).

The problem of position detecting systems for drifting buoys has a number of solutions the simplest of which, theoretically, is to relay loran signals as they are received at the buoy to a manned station where they can be compared and plotted. But loran and other pulsed radio transmissions require large bandwidths and the present areas of ground wave loran service are not very extensive. There are several phase difference methods for fixing and ranging on buoys which may be used more freely and can be operated anywhere at sea on an interrogation basis from a ship or shore point within the limits of ground wave transmission. If it ever becomes a routine matter to anchor buoys in the deep ocean, these might provide an independent reference system for either temporary hyperbolic navigation or ranging on buoys adrift. Outside the loran service areas this type of system would permit ships of buoys to work with continuous knowledge of the relative position of all points of observations, although the position with respect to the geographic coordinate system may be known with less accuracy.

In considering any such radio-location system, there is much to be gained if the ship is free to move through the buoy field making observations of other kinds. An anchored buoy reference system offers this possibility. If, however, the ship is sailed on a regular gridwork of courses, advancing with the buoys, it is possible for the position and rate of drift of the buoys to be discerned from the ship itself as the reference station. Ranges and bearings on each of a group of buoys may be repeated at intervals and if the ship has sailed along a straight course meanwhile, the ship's track provides a baseline for triangulation and ranging. These possibilities are being looked into at Woods Hole.

Beyond the problems of design of any radio telemetering system is the purely administrative problem of obtaining a suitable radio frequency allocation. According to present views, this should lie in the 1 to 3 megacycle range to provide some overlap of groundwave and skywave transmissions. Thus if a buoy drifts out of the groundwave reception area it may still be heard on skywaves. It seems improbable that pulsed signals would be permitted in this crowded range of radio frequencies because of the bandwidth requirements. Certain channels may be available, however, for continuous wave transmissions at low power. As radio telemetering systems are envisioned at the moment, the fraction of time on the air would be small but since the transmitters in the buoys would be unattended and scheduled either automatically or by interrogation from a ship, provision should be made for shutting them down in case of failure of the transmitter scheduling system. With the increasing use of aircraft in support of oceanographic ships, receivers aloft may prove useful if ranges become extreme or frequency allocations prove to be too high for successful surface reception.

Since such drifting apparatus is but an amplification of the ordinary current pole or current cross, and an ocean station is equivalent to an anchored ship, nothing very new is being tried. Yet, by adding radio to these otherwise time-honored methods, we may shift our point of observation almost at will.

APPENDIX: CURRENT MEASUREMENT*

WIND-DRIVEN SURFACE CURRENTS

To study the transfer of momentum between the air and the sea it seems necessary to be prepared to investigate both very large and very small scale phenomena. Apparatus for small scale studies of motion or the gradients of motions, temperature, and other properties through the sea surface and in waves are, to my knowledge, entirely lacking. However, some existing equipment may be useful in connection with studies of the larger scale surface motions and the vertical shear in the water phase. These are a pitot-type current meter recently devised by Willem Malkus, the current cross as used by Pritchard and Burt, and the G.E.K.

The Malkus bathypitotmeter (1953) has the form of a large bathythermograph and responds to currents in the range 50 to 250 cm/sec. It is necessary to move the ship ahead slowly if the current speeds do not fall in this range and then allow the instrument to come to equilibrium at each of a succession of depths to obtain readings. Readings on two headings must be made and composed to evaluate the resultant velocity at each level if this is not known at the start or if the current turns with depth. As far as I know there is no corresponding instrument for measuring the wind shear immediately above the sea surface although stereophotographs of vertical smoke trails have been considered.

Pritchard and Burt (1951) have found that for Reynolds numbers above 1000 the drag coefficient of a suitably weighted current cross remains constant over a usefully wide range of velocities, hence the angle of a wire supporting it is a simple function of the speed of the passing water. This convenient property of so familiar a device may have many applications as, for example, measurement of the vertical shear from a fixed or drifting station. If a recording inclinometer can be devised to accompany the current cross on its descent, it should be possible to measure vertical shear through great depths as well as small ones. Edmond Watson has constructed a device for measuring wire angle as a function of depth. This consists of a smoked glass slide moved in one direction by the action of pressure on a sylphon and a pendulum carrying a stylus to write the record of depth and incliniation. The pendulum is damped by the water which floods the instrument case. This might be adapted to cover a number of ranges of depth and might also house a recording thermograph so that the current shear and thermal gradients may be compared. Means for recording direction at great depths remain to be considered.

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* - Mr. von Arx has suggested that his remarks made in the course of the discussions following his paper be presented in these proceedings as an appendix to the main body of the paper.

Current velocity measurements by the G.E.K. (von Arx, 1950a) suffer in magnitude when the current system extends downward through more than a negligible fraction of the total depth of water (Stommel, 1948). This may be a useful limitation in connection with studies of the wind-induced surface currents generated in the open sea by passing storms since Stern (Malkus and Stern, 1952) has shown that the signal due to local accelerations of the surface circulation by the wind is added directly to those produced by steadier geostrophic circulation at greater depths. Thus, if the background level at any station could be established in a period of calms, the accelerations of the surface layers due to wind at this place may be observed. A preliminary trial of this idea has been made from one weather ship on station and Bowden (1953) in England.

Another possibility in which the limitations of the G.E.K. can be turned to good use has been pointed out from theoretical considerations by Malkus and Stern (1952) who have reinvestigated the nature of the electric potential fields associated with motion of the water of the deep sea, taking account of both the horizontal and vertical components of magnetic flux.

According to the results of this study, the difference between the integrated surface current detected by the lateral drift of a ship and the integrated lateral component of current observed by G.E.K. is equal to the mean velocity of water beneath the line of traverse. From this and a knowledge of the average depth of water under the traverse, the volume transport may be computed. In mid-latitudes and in the vicinity of the strong western-ocean currents the differences may be large enough to be measured with useful precision with existing navigational and G.E.K. equipment. If means can be developed to make precise the necessary measurements of small differences between large quantities, this technique may be a valuable one since it provides a means for making observations of the mean velocity and of the volume transport independently of the geostrophic assumption.

DEEP CURRENTS

Currents in the very deep parts of the oceans present special problems of measurement, not so much due to their inaccessibility but to their very small speed. If Kulp's figure of 1,750 years is a representative time during which this deep water may remain submerged, it then seems less likely that the circulation can be actively affected by the surface circulation through other than indirect processes. For example, if the thermocline rises and falls slowly in response to prolonged changes in the average wind stress, its variation in depth may be due either to a change in the overburden of light surface water, or the mechanism may be more directly related to the downward turbulent flux of heat. In the first case the thermocline might act as a diaphragm which shifts by displacement the very deep water masses below, while in the second case the thermocline would move but the water would not. If the first possibility is correct, and the sea level is not changed, a deepening of the level of the thermocline below the center of a light mid-ocean water mass due to increased average wind stress would be compensated by shoaling the level of the thermocline around its perimeter. The reverse effect might be expected if the average winds diminished. Such compensating motions of the thermocline would be peculiar to the diaphragm effect and thus distinguish it from the heat flux mechanism. Were the vertical motions or packing of iostherms in the thermocline to be studied synoptically by means of a grid of anchored buoys, such as those described earlier, the nature of some of the deep motions of the sea might be suggested. Still, direct measurements of the small motions at great depth would always be desirable.

GEOLOGIC PROBLEMS

Marine geological processes have direct bearing on some types of currents as well as being affected in turn by the current systems. Since the recent visit of Professor Philip Keunen to the United States, there has been more general interest in his turbidity current hypothesis published more than a decade ago (Geol. Mag., 1938). The geologic record in cores and in marine deposits exposed on land contains examples of vertically and horizontally graded coarse materials deposited conformally on fine materials. In many cases these can be explained as load deposited far from land by turbidity currents. It would be of great interest to measure a turbidity current and then to sample the deposits it has produced.

It has been suggested that a number of buoyant spheres be anchored at intervals along the foot of the continental slope so that if a turbidity current were to pass one or more of these they would break loose and float to the surface. If found on shore, the floats would call attention to a suitable area for bottom sampling and coring.

More immediate information might be gained from one or a succession of electrical cables laid parallel to the foot of the continental slope at intervals of perhaps 100 kilometers seaward. A turbidity current cutting each of these cables in turn would give a succession of signals indicating its speed of advance and an estimate of the distance run. If the cable were moved but not parted, a measurable voltage would be developed which is proportional in magnitude to the speed and in its sense to the direction of the cable's motion through the magnetic field of the earth. One long cable would indicate when a turbidity current passed but would not indicate what part of its length had become involved. Shorter cable loops would localize occurrences better. While not ideally placed, there are already a number of commercial cables across the ocean floor. The full force of motional potentials derived from the displacement of a cable in a turbidity current would either mask or disrupt telegraph service. Commerical cable companies may have records available for research or might offer opportunities for more suitable recording of the signals now regularly received.

In studies of more localized geological processes controlled by currents, movable-bed hydraulic models may serve to clarify problems of sediment transport by longshore currents and the sorting of the coarser materials over the bottom. This particular use of models would require development. Engineering use of movable-bed models is traditionally concerned with the topography of the bottom rather than the structure of sedimentary deposits produced by moving water.

ESTUARINE CIRCULATION

Studies of currents in coastal and estuarine areas is one of the traditional concerns of oceanographers. Despite the time that has been spent on the subject, very little significant progress has been made in methods for measuring of these complex current systems. The complexity of the circulation arises from the fact that there are many strong influences at work simultaneously. Broadly, these influences may be grouped as hydrologic, meteorologic, and oceanographic in nature. These groups of active forces work in confined situations so that for every parcel of water set in motion there may be simultaneously or eventually a corresponding parcel moving in reaction. The nature of the reactive motions depends to a large extent on the submarine topography of the region. The interplay of the active and reactive forces generally produces very complex circulation systems which may vary significantly from place to place and time to time within the same system. Therefore, estuarine circulations must either be studied in great detail or studied statistically.

Within the past few years progress has been made in a statistical approach to the problem of the flushing rate. Flushing, the progress of river water through an estuary, has been assumed to be indicated by the average distribution of salinity between the river mouth and the open sea. The recent theories of estuarine flushing by Ketchum (1951), Arons and Stommel (1951), Stommel and Farmer (1952), and others have been based on observations in widely different field situations such as the fjord type estuary (Tully, 1949), the coastal plane estuary (Pritchard, 1950, 1952) and the regions of the continental shelf in which the circulation is estuarine in character (Ketchum and others, 1951). The fact that this wide variety of systems yields a study from very nearly a single point of view is significant. It suggests that while the circulation systems may be quite different, the salinity distribution is achieved in much the same way in each case.

This has been explained through consideration of the combined tidal and wind-driven circulations as only a means by which the river and sea water masses are mixed within the estuary. River water tends to float stably on the salt water from the sea. As the river water moves down the estuary it becomes more saline due to salt from the sea water mixing upward from below. The net flow through the mouth of the estuary is seaward and equal to the river discharge. But since both the horizontal and vertical salinity gradients in the estuary tend to establish a more or less steady configuration, and salt is being carried out with the river water, there is a corresponding inward flux of salt water from the sea. The volumes of water exchanged to maintain the salt balance in an estuary may far exceed the river discharge during corresponding periods of time. This important mechanism seems to be present in estuaries of all kinds, though it may be obscured by the stronger action of tides, winds, branches of the offshore circulation and other effects.

A description of the manner in which mixing actually occurs and the paths followed by various parcels of water within an estuary is difficult to give fully, and is usually treated as a number of separate processes acting together. The importance of the several processes depends on the climate, the geometry of the wetted basin and the relief of the surrounding land, the tidal signature, river flow, permeability of the ground and other factors. For example, the circulation in fjord type estuaries which are deep, sheltered from the wind and often cut in hard impermeable rocks differs from the coastal plane estuaries which are generally broad and shallow, relatively unprotected from the wind, and often surrounded by soft and permeable sedimentary rocks. In fjords, wind and waves are less likely to be important influences on mixing, but the regular march of tides and changes of river discharge may control the circulation. In the coastal plane estuaries, wind, waves and tides may dominate the water motions and obscure the effects of river flow. In regions of the continental shelf where estuarine conditions exist, mixing may be strongly influenced by branches of the deep water circulation. It may be helpful to describe a few of these separate effects in turn. The current systems and mixing processes due to tidal action are often most conspicuous.

The tidal signature at the mouth of an estuary is but the beginning of what may be a complex sequence of wave motions within the embayment. Depending on the depth of water and the regularity of the boundaries, the wave may enter and travel as a single progressive wave slowly losing energy until it is damped completely, or it may be reflected back on itself. If the estuary is narrow and long the primary reflected waves are subject to analysis by the method developed by Redfield (1950). If the estuary is broad or dendritic, pairs of interfering waves may develop which set up a complex pattern of standing, progressive and rotary waves on the free surface. Since tidal currents flow in response to both the changing elevation of the free surface and the momentum acquired during their earlier history, the current may not be in phase with the wave form. To study this relationship, it is helpful to establish tide gauge stations around the perimeter of the estuary as well as to make current measurements.

In some instances the tidal currents are small and easily obscured by currents due to other causes. In such cases an intelligible synthesis of the tidal system can be gained through use of Froude models.

In other instances the tidal currents dominate the current system to the extent that the effects of river discharge, wind currents and so on, are obscure. Since the river discharge pattern is important in a consideration of the flushing rate, and the tidal motions may ebb strongly where the salinity is low and flood strongly at another place to maintain the salt balance in the estuary, it is useful to measure simultaneously the tidal volume inequality and the salinity. The observational requirements are stringent since the volumes of flow may be large and the differences small.

As though it were not enough that tides are reflected and progress in different phase than associated currents, the tidal signatures may be unsymmetrical and change progressively from day to day with the changing configuration of the astronomical bodies causing them. Semi-diurnal tides occur along most mid-latitude coasts but there are regions such as the Gulf of Mexico where diurnal tides predominate and then give way to semi-diurnal tides twice each month. Since this tidal sequence may produce a more or less complete reorganization of the tidal wave and current pattern every two weeks, rapid survey techniques are required and data for statistical treatment are best taken over at least a synodic period. Again the Froude model has served to show how the tidal circulation changes with the passage of time.

In shallow, narrow channels or estuaries through which the river discharge is large, sea water may enter as a flat wedge moving under the lighter mixed water containing the river discharge. A salt wedge intrusion influences the vertical structure of currents. Over the course of a symmetrical tidal cycle, the net flow in the salt wedge should be landward in order to carry the salt required to increase the salinity of the predominantly seaward motions of the river discharge. Since there may be a difference in temperature as well as salinity at the interface between the salt wedge and the river discharge, the position of direct current measurement stations with respect to a salt wedge may be chosen in the light of the distribution of temperature or salinity.

The consequences of the existence of a salt wedge to both the circulation and mixing of salt and fresh water have been studied intensively in recent years by Keulegan (reprinted, 1950) and by Farmer (1951) in idealized models. The staff of the Mississippi Waterways Experiment Station, Engineering Department of the University of California at Berkeley, and other laboratories, have made much longer series of observations both in the field and in models of field situations. The latter studies have been made primarily for engineering purposes, but have provided basic data that have proved valuable for tests of the statistical theories of flushing and investigations of the behavior of the salt wedge.

The jet (von Arx, 1948) is another form of intrusion that may be important in some well enclosed estuaries where wind mixing is significant, or the river discharge small. Jet flow may occur through narrow passages when the water in the estuary is mixed to the extent that the isohaline surfaces are nearly vertical and the water density at the entrance is equal to that of the sea. In this circumstance there is no stable mode of intrusion, such as the salt wedge, by which sea water may enter with the flood tide; hence the inward flow tends to be equally rapid at all levels except for the effects of bottom or side friction. In this case, too, the average ebb volume should exceed the average flood volumes by the river and ground water discharge.

Under the conditions of complete vertical mixing that favor jet flow there are opportunities for simple overturning motions to develop under wind stress. The wind-driven circulation tends to overturn in the manner somewhat like a belt on two pulleys turning on axles at right angles to the wind. In such simple systems the surface layer moves with the wind at a more or less steady speed but increases in thickness with fetch. Generally, the surface layer occupies less than half the total depth so that the upwind return current moving over the bottom is slower.

In a stratified estuary the wind-driven motions may be layered. The surface layer may have an overturning circulation of its own moving downwind on the surface and upwind along an interface which rises upwind. The frictional stress on the interface may cause the bottom layer to develop a circulation overturning in the reverse sense. It is possible that the interface may be so steeply inclined that the heavier stratum of water reaches the free surface at the upwind end of the embayment. In this case the circulation of bottom water may overturn in the same sense as the surface layer provided the circulation due to wind stress is stronger. The wind-driven and frictional driven parts of the bottom circulation may also occur as two independent cells, in which case the line along which the density interface cuts the free surface will also be a line of horizontal convergence below which water sinks.

If the wind stress produces waves with an amplitude equal to a major fraction of the total depth of water, all traces of stratification may disappear. This occurs in shallow water, sometimes to the extent that bottom sediments are caught up in the wave action. Due to the strong vertical transfer of momentum, the overturning wind-driven circulation may actually slow down even though the free surface is strongly inclined. Studies of the setup under very strong winds have been made by Haurwitz (1951), Saville (1952), and under laboratory conditions by Keulegan (1951).

A study of the wind-driven circulation of the Scotian shelf has been made recently by Longard and Banks (1952) and suggests the effect of wind on deeper, less confined water along a relatively straight coastline. Due to the fact that the circulation was less influenced by the land, the wind-induced slope of the density interfaces gave rise to longshore currents and a helical circulation in the surface layer.

Current measurements in estuaries are usually made directly although dynamic sections are also made particularly in connection with chemical investigations. Some of the instruments available for direct current measurements in estuaries and coastal waters are listed by Adams (1942), Sverdrup and others (1942), Romanovsky (1949) and von Arx (1950b). A critique of the ideal current meter has been given by O'Brien and Folsom (1948). A valuable discussion of the the use of the current pole in tidal waters has been written by Haight (1938). There is, however, a great variety of methods: sonic methods, strain gauge, capacitance and transducer methods, electromagnetic methods, dye tracers, ionization tracers, radioactive tracers, wire angle techniques, and others, which differ completely from the mechanical current meter methods that ordinarily come to mind. Many of the thermal and electrical methods were conceived to study very rapid changes in turbulent flow on a small scale. Since oceanographic observations are more generally concerned with large scale processes, clumsier methods may be more suitable. For example, the broad features of the bottom circulation in clear, shoal water can often be discerned from a study of the "sediment shadows" behind obstacles in the paths of the swiftest currents. These are often most clearly shown on aerial photographs of the estuary. Dye marker or mimeograph paper dropped from aircraft can be photographed to measure the surface currents. This technique permits large areas to be surveyed in a few hours and is especially valuable when wind stress constitutes an important driving force. It has been found that current measurements can be made with dye dropped from heavy aircraft in weather that is too boisterous for current measurements to be made successfully from anchored ships. Fluorescein dye charges must be increased when the light is poor or when the water is turbid. If fluorescein does not show plainly enough to be photographed, mimeograph paper can be used. .Mimeograph paper has the property of soaking rapidly without curling and will usually drift just under the surface. It is not capable, however, of being anchored to produce streamers and reference points in the photographs, as is fluorescein in cloth bags. In clear water on bright days it is possible to drop a weighted charge of fluorescein through the water column and in that way study the change or velocity with depth. Stereoscopic pairs of photographs can be made and if the depth of water is known the significant current velocity changes can be measured at several levels.

Models have also been used in connection with oceanographic studies of estuaries and coastal circulations. Tully (1949) and Barnes and Lincoln (in preparation) have built models of fjord type estuaries for which they found Reynolds scaling most suitable. For coastal plain estuaries, Froude scaling has been used with adjustment of the density ratio of the mixing sea and river water components by approximately the reciprocal of the vertical exaggeration (von Arx, 1950c). Models serve to guide field work in that they reveal the manner in which observations made at several points are related and often suggest where more critical observations are needed or may best be made. Aside from the field program, however, models may also serve to reveal the contribution to the whole complex circulation pattern made by each of the principle groups of forces. The effect of tides may be isolated as may be the effects of river discharge, wind force and direction, and the offshore circulation. Combinations of these may be produced experimentally to study the circumstances which produce particularly favorable or unfavorable ecological conditions or influence the flushing rates in certain restricted areas where sewage, industrial wastes or other contaminants may be pocketed.

It is interesting to note that while very great advances have been made in recent years providing statistical means for calculating the flushing rate of estuaries and the dispersal of contaminants in coastal waters, there have been no great improvements in methods for studying the circulation itself. Thus, even in relatively small scale problems of oceanography, it is difficult to reconcile the broad or statistical properties of the circulation with its active mechanisms.

DISCUSSION: Columbus O'D. Iselin

In the study of North Atlantic circulation we are finding that the law of diminishing returns has begun to set in, so far as conventional observations are concerned. A few thousand more deep temperature and salinity stations are not likely to provide much additional understanding, unless supplementary, new types of data are secured simultaneously. Thus at Woods Hole we feel that buoys hold considerable promise of filling some of our pressing needs and that their development should be pursued as vigorously as available funds permit.

The great advantage of a buoy is that it can secure a continuous record over a considerable period of time. The longer the life of the buoy, in most applications, the greater will be the returns. This means that the buoy must continue to function during periods of stormy weather. Either the buoy case must be rather large or it must be submerged below the depth of effective wave action.

Surface buoys are attractive in that they can store or transmit both meteorological and oceanographic observations. What is the optimum shape for such a buoy and how large must it be in order to ride out a gale? On the continental shelf the experience with navigation buoys is more or less applicable, but only cable ships occasionally set buoys in deep water and then for only rather short periods of time. It seems likely that a successful surface buoy must displace at least a ton. It should probably be shaped like a hydrometer and would therefore have very considerable vertical dimensions. The weakness of such a design may be that in strong winds too often a moored buoy will tow under. The very data that such a buoy could secure is needed before a convincing design study could be made. Much the same is true of the mooring problem. We can only guess at the depth and velocity of the transitory currents that the buoy will experience.

For these reasons it seems only prudent to approach the open ocean buoy problem rather cautiously, although it is in deep water that the greatest scientific returns can be expected. Experience with unmoored buoys and with buoys anchored on the continental shelf will probably indicate the most desirable characteristics of a combined meteorological and oceanographic buoy for deep water. If such a buoy could supplement or substitute for weather ships a very considerable engineering effort would be justified. By experimenting with smaller and more limited buoys oceanographers can perhaps show how feasible the more elaborate, all purpose, moored observational platform would be.

DISCUSSION: Richard H. Fleming

I have been asked to comment on Mr. von Arx's paper, although circumstances made it impossible for me to attend the symposium. After long and hard thought about what I might say, I have decided that any suggestions or ideas that were sufficiently radical or provocative would undoubtedly start an argument and that in this case I should be present in person to defend myself. Having thus alibied myself, I would like to say that the possibility of employing self-recording or telemetering buoys has been on my mind for many years and in future developments in oceanography I am positive that such devices will be used to an ever-increasing extent. The manpower in oceanography is so limited that we must employ every means at our disposal to reduce the labor of data collection and, as Mr. von Arx has pointed out, buoys can be used in certain cases to greater advantage than ships. The one thing that always worries me in proposals of this kind is the cost in man-hours involved in the development, construction and use of such equipment. All of us must consider very carefully the relative importance of developing new equipment compared to the more effective use of existing devices.

There are three points that I would like to emphasize in connection with all problems of instrumentation. First, let us carefully consider the individual job at hand before undertaking to develop a new device. I feel that even with existing instruments many are either too accurate or too complicated for the jobs for which they are actually used. Second, simplicity of construction and operation must always be kept before us. Simplicity implies economy of materials and manpower and will reduce the caliber and number of personnel required for work at sea. Third, mechanical methods of data handling must be developed to reduce the amount of manual labor currently demanded by practically all types of oceanographic observing systems before the records are in usable form. This is an old story that I have told many times and will continue to repeat until the instrument designers are conscious of the problem and will engineer their systems so that the records are obtained in a readily usuable or mechanically analyzable form. There are two related aspects to this problem that must not be forgotten. These are, to provide analyzing equipment that is capable of handling data from a variety of instruments and of a wide variety of phenomena, and to improve methods for the storage and handling of such information.

We are living in an age of gadgets. By all means let us take advantage of their help but do not let them become our masters. Our knowledge of the oceans is so fragmentary that the main problem is often to decide what to measure, not how to measure it. Instruments cannot take the place of brains and can be of real assistance only when we tell them what to do. In the present stage of development of oceanography it is essential that there be full cooperation between the theoretical worker, the field investigator, the analyst and the instrument designer. If such coordination is developed and we maintain a proper distribution of effort between them, rapid progress will be assured.

DISCUSSION: D. W. Pritchard

Mr. von Arx has in a very excellent manner described some of the possible observational techniques for increasing our knowledge of oceanic circulation. The concept of utilizing anchored or drifting buoys for collecting synoptic data has been envisioned by a number of oceanographers, but von Arx has for the first time brought together in a single paper much of the present thinking on the subject.

My brief contribution here is to suggest that many of the techniques discussed by von Arx might be advantageously pursued first through inshore and estuarine studies. In the studies of deep oceanic circulation the problems of suitable sensing elements for the parameters to be measured, of suitable recording or transmitting equipment and of suspension and anchoring of the equipment, must all be solved before successful anchored buoy stations can be utilized. In the relatively shallow water of estuaries and inshore areas some of the problems become less acute and there is an opportunity to test component parts of equipment which may later serve for deep water studies -- and at the same time obtain valuable information concerning estuarine and inshore circulation.

Despite the fact that the studies of estuaries often involve relatively small areas compared to the open ocean, the need for recording buoys in order to obtain synoptic information remains about as acute as in the case of the open sea because the time scale of transient changes is much more rapid in the estuary as compared to the open sea. Thus, though there is less area to cover in the estuary as compared to the open sea, it must be covered in much less time in order to obtain reasonably synoptic data.

As a start toward obtaining recording buoy stations for shallow water studies, the Chesapeake Bay Institute is now completing the adaptation of the CTI into a five-depth buoy recorder for temperature and conductivity. At present the device is designed to record each half hour for a period of ten days at five depths between the surface and 150 feet. Also nearing completion is a current meter which will record the magnitude and direction of the water motion each half hour for a ten day period. This latter unit is designed especially for inshore studies where fouling of moving parts of the conventional current meters presents a problem. The CBI device has no moving parts, utilizing acoustical means to obtain the water velocity.

Dr. Fleming, in his comments on this subject, has warned against placing too much emphasis and effort on instrumentation as opposed to utilizing the facilities we now have to increase our fragmentary knowledge of the oceans. From my viewpoint the lack of suitable instruments remains one of the most critical factors in holding back our proper understanding of the physical phenomena occurring in the ocean and the inshore areas bordering the ocean. Almost every theoretical attempt to explain circulation or diffusion in the ocean or the inshore waters requires for ultimate proof or disproof observations which cannot be obtained with present facilities.

One last comment on desirable instrumentation for shallow water studies which may have general application in oceanography. Our knowledge of the spectrum of turbulent motion in the ocean is almost completely lacking. The possibility of observing this spectrum in the open sea appears somewhat remote, since suitably securing the sensing elements would be almost impossible. Some information might be obtained in shallow water through the use of towers secured to the bottom, much as the turbulence in the lower layers of the atmosphere is studied. The tower, with suitable sensing elements attached, could be constructed on a pontoon barge, which could then be towed to a suitable location, the pontoons flooded, and the assembly sunk into position. When the operation is completed, aqualung swimmers could be utilized to attach air hoses to the pontoons and the assembly could be refloated, to be used in another location. Measurements obtained from such an installation could be used to check the indirect determinations of the non-advective flux of momentum and salt in estuaries, and would be very valuable in the further development of flushing theories.

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Contribution No. 691

Särtryck ur Tellus nr 1, 1954.

Photographic Investigation of the Projection of Droplets by Bubbles Bursting at a Water Surface[1]

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Abstract

Bubbles of air reaching the air-water interface burst and eject liquid droplets into the air to heights large compared to their diameter. Photographic evidence is introduced to prove the existence of a jet of liquid which upon breaking up produces these droplets. The jet is shown to be produced by the collapse of the bubble cavity.

The droplets are found to be of the order of one tenth of the bubble size, for the range investigated (0.2 to 1.8 mm diameter), each bubble producing about 5 droplets.

The droplet-producing mechanism is essentially the same for fresh and sea water or sea water with oleic acid surface film. The time required for the bubble to burst and the jet formation to take place is found to be proportional to the bubble size. The sea water droplets produced by this mechanism leave, upon evaporation of the water, salt nuclei having the size range observed by WOODCOCK (1952).

It is suggested that such bursting of bubbles plays an important role in the natural production of air-borne sea-salt nuclei at the sea surface.

1. Introduction

Among meteorologists it has long been recognized that airborne chloride particles may play an important role in fog, cloud and precipitation processes.

KINCH (1887) and many other workers at widely different geographical locations have found chloride in rain waters. KÖHLER (1936) and HOUGHTON and RADFORD (1938) measured chloride in cloud and fog waters, which they attributed to the presence in the air of sea-salt nuclei on which the cloud and fog droplets formed. OWENS (1926) measured the sizes of some of the larger salt particles found in clear air near the sea surface, and WOODCOCK (1952) extended the range of salt particle size measured and showed that these particles are also present in clear air at cloud levels. It is the purpose of the present study to show that the mechanism of the bursting of small bubbles at the sea surface can account for the initial introduction of sea-salt nuclei into the air.

All of the above authors recognized that the sea surface was the source of the chlorides measured. KÖHLER (1941) proposed that the formation of spray at wave crests by strong winds was responsible for airborne salt nuclei. FACY (1951) suggested that rupturing of bubble films produce the observed weights of nuclei. STUHLMAN (1932) had previously suggested that the bursting of bubbles in distilled water produced jets (similar to "Worthington's Splashes") which broke into small droplets. The present study proves that jets occur when

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small bubbles burst at the surface of fresh water and sea water. It is shown that the jets formed in sea water can account for a large portion of the range of weight of the salt particles observed in the free air. The relative percentage of the naturally occurring salt nuclei which originate from the break-up of jets and from other mechanisms remains to be investigated. High speed photography has been the primary tool in carrying out the present study.

2. Photographic Observation of Bursting Bubbles

As previously pointed out, STUHLMAN (1932) has suggested that the formation of a jet on the bursting of a bubble is the principle mechanism by which droplets are ejected into the air. In this investigation bursting bubbles (diameter 0.2 to 1.8 mm) in fresh and sea water were photographed from above and below the surface, in an effort to examine in more detail the mechanism proposed by Stuhlman.

Figure 1 shows still photographs (less than 30 microseconds exposure time) of one millimeter bubbles bursting in fresh water. The sequence has been established by comparison with high speed motion pictures. These photographs were made in an unsuccessful attempt to observe the rupture of the bubble surface film. The exposure time was much too long to stop this exceedingly rapid phenomenon. It is significant, however, that no droplets of large enough size to be resolved by the film and optical system were observed from bubbles of this size until *after* the jet formation. This is thought to indicate that the larger droplets are not produced when the bubble film is broken.

The initial burst of the bubble is observed as a slight wave train starting outward. The mouth of the cavity widens until it is almost twice the initial size. The jet suddenly projects upward, continues to rise as a thin column, and then the unstable column breaks into droplets of varying size. In general the last droplet to leave the jet has very little vertical motion and rapidly returns to the surface. The jet finally collapses completely, and the surface where the jet action occurred becomes completely smooth, without further oscillation.

The horizontal views in Figures 2 and 3 show the collapse of the cavity prior to the formation of the jet. These sequences indicate how a jet forms from a conical depression which, in turn, is formed from the initial spherical cavity. In the time interval from the initial rupture of the film until the depression has assumed a conical shape, a disturbance (probably associated with the drawing back of the upper lip of the cavity by surface tension) is observed to propagate downward along the bubble surface. Figures 2 and 3 are photographs of different, but exactly similar, events. Since the exposures are of slightly different phase, a combination of two sequences gives a fairly detailed picture of the successive stages of bubble collapse and jet droplet formation. (The two or three motionless droplets, which appear in these photographs, are adhering to the inner surface of the glass wall and were produced by jets from other bubbles.)

Figures 2 and 3 strongly suggest that the dynamics of the jet, the size of projected droplets, and the height reached by the droplets are determined by the shape and hydrodynamics of collapse of the cavity itself. Very large mass velocities are probably associated with the converging flow at the vertex of the cone. The extremely rapid withdrawal of the lip of the cavity, considerably prior to formation of the jet, leaves little foundation for STUHLMAN's (1932) proposed mechanism of jet formation under a "sucking" influence of a vortex ring formed by the ejected bubble gases.

It can be observed, in the last two pictures of Figure 3 (arrow) and in other photographs, that a barely visible small droplet is projected between two larger ones. These microscopic droplets are doubtlessly formed in the break-up of the jet. Similar phenomena have been photographed by other investigators in the break-up of a falling jet of water and in the break-up of raindrops. In other photographs (not published) large droplets were observed to strike the water surface and rebound with a much reduced diameter. These two phenomena, associated with the bursting of relatively large bubbles, indicate that these bubbles also produce the smaller-sized air-borne sea salt nuclei.

Figures 1, 2 and 3 show jets formed at the surface of tap water. Do the bursting of bubbles and the formation of the jet change

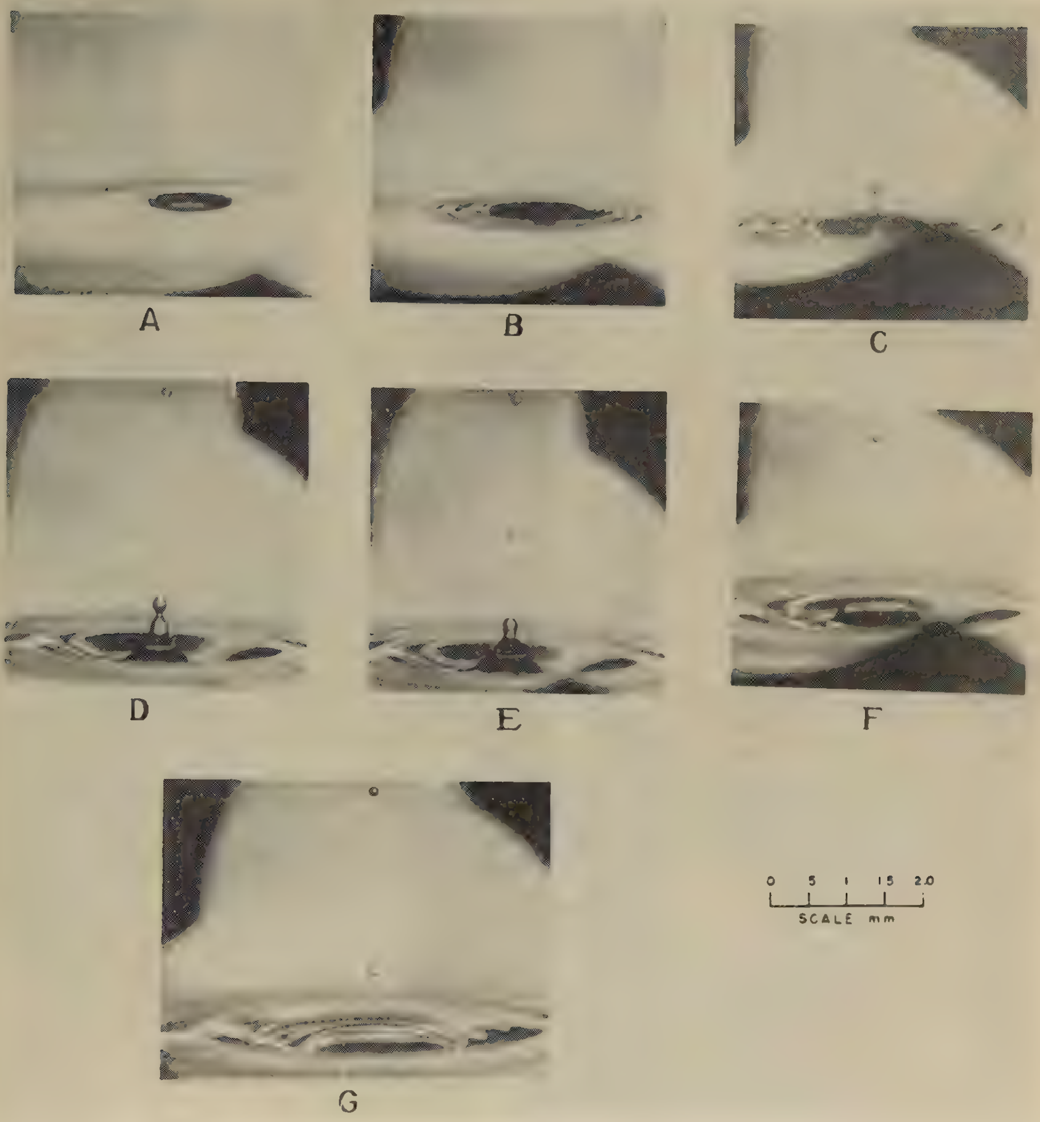

Fig. 1. Still photographs of 1.0 mm diameter bubbles bursting in fresh water. The sequence is based on comparison with high speed motion pictures. Angle of view about 10° below the horizontal. Exposure time ca. 30 μ sec. Time interval between pictures uncertain.

a. Bubble approaching surface.
b. Bubble just after rupture.
c. Initial rise of jet.
d, e, f, and g. Projection of droplets and decay of jet.

appreciably in salt water or in water with a contaminated surface? Similar photographs under various conditions indicate there is no significant change in the collapse of the cavity, or formation and break-up of the jet. In sea water the only marked difference was that a much longer period of time elapsed between the arrival at the surface and the bursting of the bubble. A second bubble from the source would arrive at the surface before the previous one had burst.

Compressed films of oleic acid on a sea

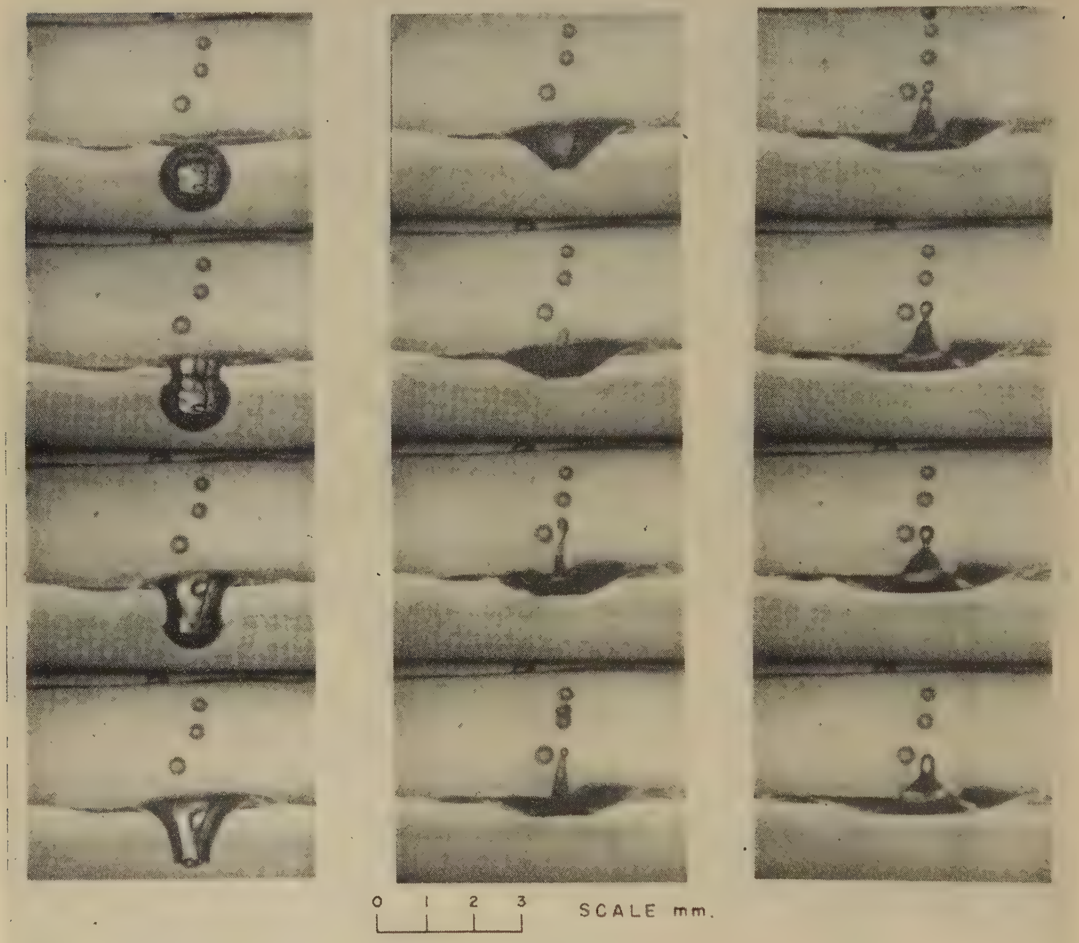

Fig. 2. High speed motion pictures of 1.5 mm diameter bubbles bursting in fresh water with clean surface. Angle of view horizontal through glass wall formed by glass microscope slide. Camera speed 3340 frames/sec.

water surface lower the surface tension and were observed to reduce the period of time spent by the bubble at the surface before bursting.

What is the effect of change in bubble size on the bursting mechanism? Observations of 0.4 mm bubbles in tap water, indicated that in general the picture was the same as that for the 1.7 mm bubbles. However, the time from initial burst to collapse of jet is considerably shorter than that of the larger bubbles. Measurements from photographs indicate that the total time is proportional to the bubble size. It was observed that the larger droplets sometimes bounce once or twice, when they hit the surface, whereas the small ones are not observed to do so.

In working with a still smaller bubble size (0.2 mm) in clean salt water, it was found that these small bubbles accumulate at the surface, forming a patch, the bursting occurring at random, and the jet formation and collapse taking place so rapidly as to be virtually incapable of resolution with the photographic techniques available to us. Oleic acid applied to the surface again produced the effect of shortening the time required for the rupture of the bubble.

Occasionally bubbles collide, forming a larger bubble by coalescence. This merging of bubbles is sometimes observed to produce oscillations which bring about the formation of other much smaller bubbles.

Measurements of droplet sizes formed by all the different bubbles used in this investigation indicate that the average drop size is approximately one tenth the bubble size. Figure 1 D shows the usual range of droplet size variation found from individual jets. Each bubble jet produces about 5 droplets.

Woodcock (1952) gives a table of observed sea salt nuclei and the corresponding droplet diameters at sea-water concentrations. These data are reproduced on Table 1 together with a list of bubble diameters which would be expected to produce the corresponding droplets. The inference that may be drawn from Table I is that a bubble spectrum below 1.8 mm diameter could produce the observed spectrum of air-borne sea-salt nuclei. This result is consistant with Stuhlman's (1932) observation that "for bubble diameter greater than 0.24 cm . . . . the ejection of the droplets was not of sufficient regularity to warrant quantitative interpretation".

Table 1. Diameter of bubbles which would produce sea-salt particles of sizes observed in the atmosphere.

Weight of sea-salt nucleus (micro-micro gms.)	Diameter of sea water droplet from which nucleus is derived (microns)	Approx. diameter of bubble which would produce corresp. droplet (microns)
1	3.8	40
10	8.1	80
10^2	17.4	170
10^3	37.6	380
10^4	91.0	910
10^5	174.0	1 700

3. Summary of Conclusions

1. The bursting of a bubble at the air-water interface in sea water or fresh water produces droplets that are ejected upward to heights large compared to the bubble size. The mechanism by which the droplets are formed and given an initial vertical velocity is found to be a result of the formation and break-up of a jet of liquid which evolves from the collapsing bubble. The energy associated with the jet formation and break-up is principally derived from the collapse of the bubble cavity some time after initial rupture of the surface film.

2. The essential mechanism of bubble bursting and jet formation and break-up is not changed with bubble diameter over the range investigated (0.2 – 1.8 mm). The total time required from rupture to decay of the jet was found to be proportional to the bubble size.

3. Bubbles bursting in sea water present essntially the same picture as those bursting in fresh water with the exception that a much longer period of time is required to rupture the bubble in sea water. Oleic acid on the surface has no observable effect other than to reduce the time between arrival of the bubble at the surface and the bursting of the bubble.

4. The droplets produced by bubbles up to 1.8 mm in diameter (the upper limit for optimum droplet production) are of the order of 1/10 the bubble size. This range of bubble size corresponds to a salt nucleus weight range observed in the atmosphere.

5. Occasionally, large bubbles are observed to produce much smaller droplets than those normally encountered. They appear simultaneously with the larger droplets. Also large droplets have been observed to reduce their mass upon rebound from the surface. These two methods suggest that large bubbles also are directly responsible for some of the lighter salt nuclei.

6. There is strong photographic evidence that the bursting of small bubbles plays an important role in the production of particles of the size range commonly encountered in the atmosphere. The jet mechanism is the only method of droplet production which has been considered here. The rupture of the film on these small bubbles may produce other much smaller particles. This question could not be investigated by our methods.

4. Experimental Techniques

Two types of photographic observation were made in this investigation (a) still photographs of very short exposure time (ca 30 microsec.), taken at random during the bursitng of a stream of bubbles, and (b) high speed motion pictures (ca 3,000 frames per sec.) of individual bubble bursts taken with an Eastman camera.

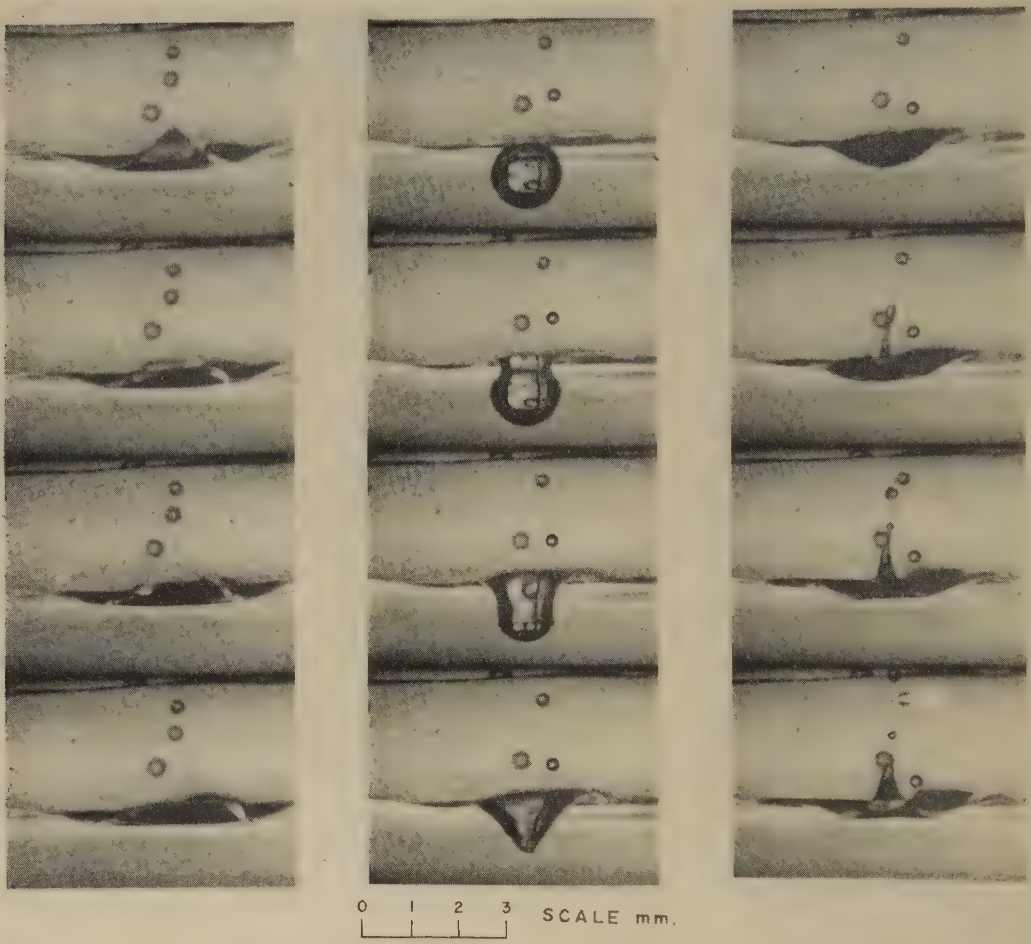

Fig. 3. First four frames at left show the final stages in the collapse of the jet shown in figure 2. The four frames in the middle and at the right were made with the camera speed 3 000 frames sec; other conditions being like those given for figure 2.
Note the barely resolvable droplet indicated by the marker at the lower right.

The photographic equipment for the still pictures consisted of an Argus C-3, 35 mm camera with a Cinter 50 mm lens on a 165 mm lens extension tube. The magnification of the lens system is 3.3 diameters. The light source was a General Radio Strobolux, Model 648-A. This model Strobolux is rated for a duration of flash of less than 30 microseconds with a flashing rate up to 100 flashes per second.

The high speed pictures were made with an Eastman Highspeed camera type III, which used 100 ft rolls of 16 mm film. The lens system for this camera was a Kodak Anastigmat f2.7, 63 mm lens and a 105 mm lens extension. The effective magnification was 1.7 diameters. A photospot (No. RSP2) lamp, at close range, was used as a light source. The Eastman Highspeed has a frame exposure time of one fifth the picture cycle, and, since the average speed was near 3,000 frames per second, the average exposure was about 65 microseconds.

In both the stroboscopic and high speed photographs, back lighting was used. Light reflected by a mirror from the light source was directed through the bubble into the lens. It was found that this method produced enough illumination to enable the use of a small aperture with both cameras.

The bubbles were formed at the end of a drawn out glass capillary placed 10—20 mm. below the liquid surface. The bubble size was varied by changing either the tip size or air pressure. The liquids used in this investigation were tap water, sea water and sea water with the surface modified with a compressed film of oleic acid. The fresh and sea water surfaces were flushed prior to photographing and free from known surface contamination. The bulk liquid temperature was in general at the ambient air temperature which varied from 21° C to 25° C.

The horizontal photographs of the bubbles bursting at the surface were taken through a glass microscope slide that had been placed in the glass jar that contained the bubble source. The inner surface had been previously coated with General Electric Dri-film to reduce the rise of the meniscus along the slide.

5. Acknowledgments

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DEEP WATER ELASMOBRANCHS AND CHIMAEROIDS FROM THE NORTHWESTERN ATLANTIC SLOPE

by

Henry B. Bigelow

and

William C. Schroeder

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No. 2 — *Deep Water Elasmobranchs and Chimaeroids From the Northwestern Atlantic Slope*[1]

By Henry B. Bigelow and William C. Schroeder

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[1] Contribution No. 692 from the Woods Hole Oceanographic Institution.

INTRODUCTION

The slope of the bottom is so steep from the edge of the continent at the 150-200 fathom level down to the 800-900 fathom level off the northeastern United States and off Nova Scotia that the intervening zone is not wider than about 25 miles, anywhere between the offing of Chesapeake Bay and the Laurentian Channel, with a minimum breadth of only 7-10 miles. Nevertheless this zone, narrow though it be, is of great interest ecologically, because it is the site of the transition from the bottom-dwelling animals of the shallow waters of the continental shelf, to those of the Atlantic abyss.

The explorations by the ''Blake,'' and especially those by the ''Albatross'' in the 1880's, yielded a wide variety of bottom-living fishes from the lower part of the slope at depths of 800 fathoms and more; they also sampled the bathypelagic communities of the overlying waters, many additional members of which have been brought to light subsequently. The fishes, too, of the northeastern American shelf have been studied intensively at many hands for many years, not only from the descriptive-taxonomic standpoint, but also from the standpoint of the commercial fisheries.

But the ''Albatross'' and ''Fish Hawk'' devoted less attention to the middle part of the slope. (They made only 63 trawl hauls at 250-500 fathoms, contrasted with 117 hauls deeper than 700 fathoms). And no subsequent attempt has been made to continue the scientific investigation of the bottom-living fishes in deep water in the northwestern Atlantic since 1887 when the ''Albatross'' was transferred to the Pacific, whether because of the expense that would have been involved, or because of a shift of interest to other subjects. And very little commercial fishing, either with hook and line or with the trawl, has ever been attempted deeper than about 250 fathoms along the slope with which we are concerned, partly because of the difficulty and expense of operating commercial gear in greater depths, and partly because it has not seemed likely that saleable food fishes would be found on bottom there in worthwhile quantities.

Consequently, while it seemed safe to forecast, from the fish faunae of shallow water and of deeper, what species of bottom fishes might be expected along the mid zone of the slope, the belt in question was a *mare incognitum,* to all intents and purposes, as regards the quantities of any species to be found there.

In the hope of filling this gap in our knowledge, trawling campaigns were carried out by the Woods Hole Oceanographic Institution along the slope between the offings of southern New England and of La Have Bank, Nova Scotia, on the "Caryn" in June and September 1949; between the offings of Montauk, Long Island, New York, and of La Have Bank from the dragger "Cap'n Bill II" in June and July 1952; and between the offings of Virginia and of La Have Bank on "Cap'n Bill II" in June and July 1953. Otter trawls 35 feet wide were used in 1949, 35 and 50 ft. trawls in 1952, and 60 ft. trawls in 1953. One hundred and forty-three successful hauls were made in the three summers combined, dragging on bottom for 30-60 minutes, between 200 fathoms and 730 fathoms. And a total catch of about 25,000 bottom fishes in all the hauls combined seems good evidence that the nets worked with at least moderate efficiency.

The present report deals with the catches of elasmobranchs and of chimaeroids.

The following species of sharks and skates had been reported, through 1953, from depths greater than 200 fathoms on the American Atlantic slope north of Chesapeake Bay: *Apristurus profundorum* Goode and Bean 1895; *Centroscyllium fabricii* (Reinhardt) 1825; *Etmopterus princeps* Collett 1904; *Centroscymnus coelolepis* Bocage and Capello 1864; *Raja bathyphila* Holt and Byrne 1908; *Raja jenseni* Bigelow and Schroeder 1950; *R. mollis* Bigelow and Schroeder, 1950; *R. laevis* Mitchill 1817; *R. senta* Garman 1885; and *R. spinicauda* Jensen 1914. On the other hand, one species — *Scymnodon melas* — described by Bigelow, Schroeder and Springer (1953, p. 233) as new must now be relegated to synonymy (p. 51).

The trawling operations of "Cap'n Bill II" add *R. fyllae* Lütken 1887 to this list. And it is likely that *R. hyperborea* Collett 1878 will be found off Labrador or off Newfoundland sooner or later. But the number of trawl-hauls that have been made along the 300-550 fathom zone between the Hudson Canyon and the offing of La Have Bank, Nova Scotia, is now so large that the list of elasmobranchs to be found on the bottom there is not likely to be increased much in the future.

SHARKS

Family SCYLIORHINIDAE
Cat Sharks

APRISTURUS PROFUNDORUM (Goode and Bean) 1895

This deep-water shark had been known from two specimens only, both of them from the offing of Delaware Bay, until the summer of 1952 when "Cap'n Bill II" trawled it at 7 stations (8 specimens) scattered along the slope from the offing of New York (Lat. 39°46′N, Long. 71°35′W) to the offing of southern Nova Scotia (Lat. 42°39′N, Long. 63°54′W). And with 8 more, taken in 1953 at 6 stations, the records for it are numerous enough now and distributed widely enough to show that it is to be found generally, though sparsely, along the slope from the offing of Nova Scotia to that of Virginia (most southerly station, Lat. 37°39′N, Long. 74°06′W; most northerly, Lat. 42°40′N, Long. 63°52′W). The depths of capture range between 360-420 fathoms and 640-720 fathoms for the two years combined. The temperature on bottom, at the stations where it was taken, was 3.7° to 4.5°C in 1953, and presumably was about the same in 1952, though no bottom readings were taken that year at the particular localities in question.

Points of taxonomic interest are discussed in our earlier paper (Bigelow, Schroeder and Springer, 1953, p. 214).

Family SQUALIDAE
Spiny Dogfishes

CENTROSCYLLIUM FABRICII (Reinhardt) 1825
Black Dogfish

Earlier captures of the black dogfish on the slopes of the Nova Scotian Banks, and of Georges Bank, had not been numerous enough to suggest the existence of more than a sparse population there, though a widespread one as had been known for many years. In fact, only two specimens had come into our hands, in the Museum of Comparative Zoology, at the time when our earlier discussion of its occurrence in the western Atlantic was written (Bigelow and Schroeder, 1948a, p. 486). But catches of 69 black dogfishes by "Caryn" in 1949, and of 715 and 371 of them by "Cap'n

Bill II" in 1952 and 1953 respectively, show that our previous estimate of its numbers off Nova Scotia and off Georges Bank must be revised upward. This seems, indeed, to be the most plentiful shark there at depths greater than those frequented by the common spiny dogfish (*Squalus acanthias*).

No doubt the reason for the quantitative discrepancy between the older records for the species in Nova Scotia slope waters, and the catches of it made there in 1949, 1952 and 1953 is that all of the former were based on fish taken with hook and line by the halibut fleet which did not fish much below 200 fathoms, i.e. not deep enough to sample more than the uppermost fringe of the population of this deep-water shark.

The number of specimens at hand is now large enough to throw some light on the quantitative occurrence of the species, both geographic and bathymetric. The average catches, per successful haul,[1] within the depth range where *fabricii* was taken at all, were about 24 specimens to the eastward of longitude 66°W for the years 1949, 1952 and 1953 combined (49 hauls); between 4 and 5 specimens from longitude 66° to longitude 69°59′W (26 hauls); 2 specimens from longitude 70° to longitude 71°59′ (10 hauls); and about 1 specimen westward and southward thence to the offing of Virginia (12 hauls). Similarly, the largest catches made in any one haul were 92 and 95 specimens east of longitude 66°; 29 between longitudes 66° and 69°59′W; 8 between longitudes 70° and 71°59′W; and 3 farther to the west and south. The regularity, too, with which *fabricii* was taken shows a corresponding gradient from northeast to southwest, for while 97 per cent of the hauls made in 1952 and 1953, within its preferred depth zone, yielded it to the eastward of longitude 66°, only 65 per cent did so along the slope off Georges Bank (longitudes 66° to 69°59′); 60 per cent in the offing of southern New England (longitudes 70° to 71°59′); and 50 per cent farther westward and southward.

Evidently, then, the center of abundance for *fabricii*, in American waters, lies at least as far to the eastward and northward as the offing of western Nova Scotia, perhaps farther still in that direction. Even here, however, the black dogfish — like other fishes — vary widely in numbers from place to place within

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[1] We take no account of such of the hauls as obviously were unsuccessful for one reason or another.

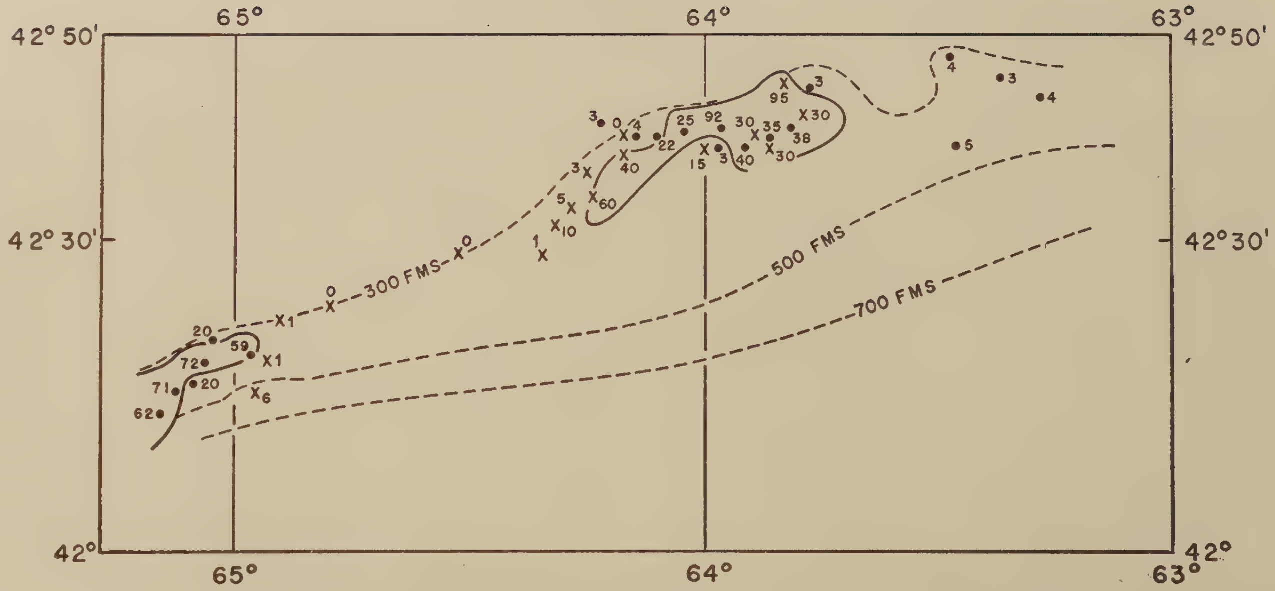
65°
64°
63°
42° 50'
42° 30'
42°
300 FMS
500 FMS
700 FMS

Fig. 1. *Centroscyllium fabricii.* Numbers per haul taken east of longitude 66°W in 1952 (•) and in 1953 (x). The solid curves enclose the areas where the catches per haul were consistently greater than 25.

short distances, independent of the precise depth, as is illustrated by catches ranging from 3 to 92 per haul within a distance of about 5 miles along the 340 to 520 fathom zone between longitudes 63°58′ and 64°06′ in 1952; from 15 to 95 per haul within about 10 miles in that same general region in 310 to 625 fathoms between 63°50′ an 64°00′ in 1953; and from 5 to 40 within a few miles to the southwestward (longitudes 64°10′ to 64°17′; 280 to 475 fathoms) that same summer. But a plot of the catches made per haul (Fig. 1) shows that these were not haphazard, for in each year there was a definite center of abundance, concentrating at about longitudes 63°50′ to 64°10′, extending for something like 30 miles along the slope between 310 and 545 fathoms, with the bottom less productive both to the northeastward and to the southwestward. And a similar concentration was encountered some 35-40 miles to the southwestward (longitude 65° to 65°10′) in 1952 at about that same depth (310-490 fathoms). This precise locality was not revisited in 1953. The discovery of these rather definite centers of population is of general interest as evidence that the relative productivity of the bottom, in fishes, may vary as widely from place to place, far down the slope, as every fisherman knows that it does on the great fishing banks on the continental shelf.

It may be worth adding that an average catch of 21 specimens per haul, with the trawls used, would work out at about 4 specimens per acre, the richest catches (92 and 95 per haul) at about 18 per acre — if the trawls caught all the specimens lying in their path, which they certainly did not; how much to add for failure in this respect would be sheer guesswork.

If the catches can be taken at face value, *fabricii* is only about ⅕-⅙ as numerous along the slope of Georges Bank and off southern New England as it is off Nova Scotia, and still less numerous farther to the west and south.

Nevertheless, captures of five specimens off Delaware Bay in 3 hauls (Lat. 38°41′N-38°47′N), of one off the coast of Maryland (Lat. 38°05′N), and of one off the coast of Virginia (Lat. 37°39′N) show that *fabricii* ranges farther to the southward, along the American Atlantic slope, than had been known previously.

Off Nova Scotia, the shoalest capture of *fabricii* was in a haul at

185-220 fathoms (3 specimens); the largest catches (92 and 95 specimens) were made between 310 and 360 fathoms; and the species seems to have been distributed rather uniformly down to about 600 fathoms, to judge from average catches of about 28 per haul at 301-400 fathoms, of 22 at 401-500 fathoms, and of 33 at 501-600 fathoms. But catches of only 15 in a haul at 610-625 fathoms, and 6 in one made at 660-705 fathoms[1] suggest that *fabricii* is less plentiful deeper than 550 fathoms than shoaler. But average numbers of specimens taken per haul at different depths may be deceptive, if taken by themselves, for they conceal the fact that the numbers caught, in individual hauls, varied about as widely within representative depth zones as they did geographically (Fig. 1), no doubt for the same reason.

Maximum and minimum numbers caught per haul, east of longitude 66°W, in 1949, 1952 and 1953 combined, at depths greater than 300 fathoms, are as follows:

Depth in fathoms	Number of hauls	*Fabricii* caught per haul
301 - 350	12	3 - 95
351 - 400	6	4 - 71
401 - 450	7	0 - 59
451 - 500	6	1 - 40
501 - 550	4	3 - 62
551 - 600	1	5
601 - 650	1	15
651 - 700	1	6

Farther to the west and south *fabricii* is not only less numerous, but the upper boundary to its vertical range lies deeper down the slope, progressively. Thus the shoalest hauls in which it was taken were at 355-400 fathoms (1 specimen) and 360-420 fathoms (2 specimens) along the slope of Georges Bank, at 390-460 fathoms (3 specimens in 3 hauls) in the offing of southern Massachusetts, and 485-520 fathoms, southward from the offing of New York.

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[1] These were the only hauls to the eastward of longitude 66° that worked as deep as 600 fathoms, either in 1952 or in 1953.

The deepest catches were made at 660-705 fathoms off Nova Scotia (6 specimens in one haul); at 600-670 fathoms off Georges Bank (5 specimens in 1 haul); at 710-730 fathoms off southern Massachusetts (5 specimens in 1 haul); at 630-675 fathoms (3 specimens in 1 haul) and at 640-720 fathoms (2 specimens in 1 haul) farther to the westward and southward. As these were the deepest successful hauls, with one exception, that were made in the respective sectors of the slope, it is a question for the future how much deeper the range of *fabricii* may extend.

In 1953, when the temperature was taken on bottom with maximum-minimum thermometers at almost all the stations where trawl hauls were made, all the captures of *fabricii* occurred where bottom temperatures ranged between about 4.5°C, and about 3.3°C, the great majority between 4.5° and 3.9°. And even if the range of *fabricii* reaches down as deep, say, as 1200 fathoms — of which there is no evidence — its lower thermal boundary along the American slope would not be colder than about 2.5°C. At the other extreme, specimens that work their way up the Nova Scotian slope to 200 fathoms or so, such as were brought in by the halibut fleet years ago, are likely to meet water at least as warm as 6-7°C. Thus, the range of temperature within which it occurs in greatest numbers in American waters is only about 2°C, the extreme range there perhaps 4-5°C for the entire population.

Consequent on the steepness of the slope, the maximum breadth of the zone where *fabricii* occurs the most regularly is only something like 25-30 miles off the Grand Banks and off Nova Scotia, even if it ranges down to 1000 fathoms there; 10-12 miles along Georges Bank and off southern New England; and perhaps 15 miles in the offing of Maryland and of Virginia.

The catches of *fabricii* made east of longitude 66°W averaged considerably larger in 1952 than in 1953 as tabulated below. But with the catches in individual hauls ranging from 1 to upwards of 90 in each of the two years, the discrepancy may not be wider than can be credited to what we may call "fisherman's luck," for want of a better name.

Catches east of longitude 66°W, at depths greater than 300 fathoms

	Successful hauls	Hauls with *fabricii*	Percentage of hauls with *fabricii*	Total catches	Average per haul	Maximum catch
1952	19	19	100%	610	32	92
1953	15	14	93%	333	22	95

Among 25 specimens that were opened in 1953, 10 were empty; the others contained remains of fishes, decapod crustaceans, (shrimps), schizopod or euphausiid, squids, and octopus.[1]

ETMOPTERUS PRINCEPS Collett 1904

We have already reported (with description) the capture of 47 specimens of this deep-water shark along the slope between the offings of southern New England and western Nova Scotia (Bigelow, Schroeder and Springer, 1953, p. 47). Earlier records for *princeps* had been from the Faroes-Hebrides region (Collett, 1904, p. 3; 1905, p. 28) and from the offing of the Straits of Gibraltar (Koefoed, 1927, p. 21). The trawlings of 1953 yielded 7 more, all of them from the offing of western Nova Scotia. The largest numbers taken were 9 (once), 8 (once) and 7 (once) while 1 was the number taken the most often (fourteen times).

The hauls that took *princeps,* in the three seasons, were at depths ranging from 310-320 fathoms down to 490-540 fathoms, with the largest catches (7, 8 and 9) at 480-520 fathoms, 420-480 fathoms, and 390-440 fathoms respectively, which suggests that *princeps* is about equally plentiful, downward, across the depth zone along which it occurs off our coasts. And it is to be expected considerably deeper there as well, for it has been taken at 1134 fathoms off the Straits of Gibraltar.

The 18 hauls that yielded it in 1949 and 1952 were scattered all along from the offing of La Have Bank (longitude 63°38′W) to the offing of Cape Cod (longitude 70°05′W), with the largest catches (3, 7, 8 and 9 individuals) off Nova Scotia. Similarly, 5 of the 7 specimens taken in 1953 were from the general offing of La Have Bank, only 2 off the eastern part of Georges Bank, although many successful hauls were made there and to the westward along the 300-550 fathom zone that summer. It is a question for the future whether this difference is evidence of a corresponding fluctuation in the western boundary of *princeps*, in numbers large enough for the trawl to pick it up, or whether we are dealing with a matter of pure chance. In either case, there is nothing to suggest that this shark ranges westward beyond the offing of Cape Cod, a limitation we cannot explain as due to temperature, for readings taken by "Cap'n Bill II" in 1953 on bottom along the 300-550 fathom zone were very nearly the same to the westward of longitude 70°W (3.5°-4.8°) as to the eastward (3.3°-4.5°).

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[1] Stomach contents identified by Dr. Benjamin Laevitt.

CENTROSCYMNUS COELOLEPIS Bocage and Capello 1864
Portuguese shark

The trawlings of 1953 yielded three specimens of this species: two juvenile males, 565 mm. and 690 mm. long, and an adult female of 1035 mm. which gave premature birth on deck to 15 embryos 266-282 mm. long, 5 of them males and 10 females. The number of embryos is in line with Vaillant's (1888, p. 66) record of 13 to 15 for this species. Moreau (1891, p. 9), it is true, has reported only 5 for a Mediterranean female, identified as *coelolepis*, but her small size (599 mm.) suggests that she belonged to some other species in reality.

It has been a tacit assumption, until recently, among students of sharks, that the denticles which develop on any given part of the body at different stages of growth are similar in shape; hence, that the shape of the denticles is a more or less reliable specific character — or even a generic one. But Radcliffe (1916, p. 267) has pointed out that the denticles to be seen on specimens of different ages differ somewhat in shape in some species of the genus *Carcharhinus*. Tortonese, too, (1952, p. 386, fig. 1; p. 387) has recently found that the denticles on the sides of a juvenile male, 270 mm. long, seemingly referable to *Centroscymnus coelolepis* by other characters, were strongly tridentate, whereas those on the adult *coelolepis* have evenly rounded edges, as has been known for many years. And the "Cap'n Bill II" series of that species enables us to corroborate his very interesting finding. Thus those on the body of our adult female 1035 mm. long are evenly ovoid in outline, with concave crowns, and regularly overlapping (Fig. 2*D*); they have been pictured and described similarly for this species by Bocage and Capello (1866, pl. 3, fig. 3), by Vaillant (1888, pp. 64-65), by Garman (1913, pl. 14, fig. 8), and by us (1948a, p. 495, fig. 94A). But the denticles on the embryos to which she gave birth[1] are tridentate, weakly so on the top of the head, where they are moderately widely spaced, but much more strongly tridentate on the sides of the body where they are more widely spaced as well (Fig. 2*A*).

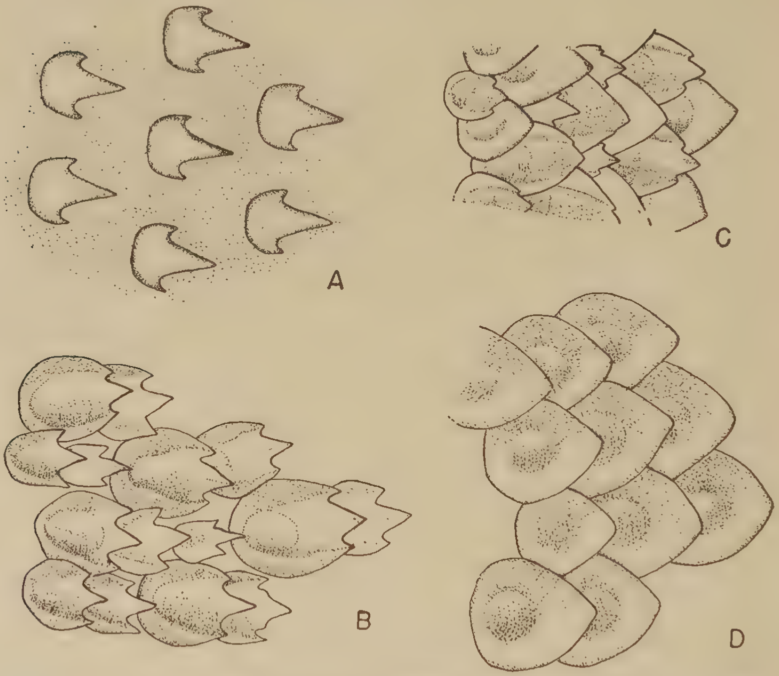

Fig. 2. *Centroscymnus coelolepis.* Dermal denticles from side of trunk below first dorsal fin. *A*, Embryo male, 282 mm. long, from adult female of 1035 mm., about 13 x. *B*, Juvenile male, 565 mm. long, about 8 x. *C*, Juvenile male, 690 mm. long, about 6 x. *D*, Adult female 1035 mm. long (mother of embryo shown in *A*), about 5 x.

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[1] Embryos well formed, but with only the tips of the teeth exposed, while the denticles had not yet erupted through the skin.

It is evident, too, from partly grown specimens of different sizes that the margins of the denticles that are developed successively, during growth, are less and less dentate. The smaller of the denticles, for example, on the flanks and belly of a juvenile male 565 mm. long are strongly tridentate still, but the larger (i.e. younger) ones only weakly so, and with one overlapping the next more or less widely in most cases (Fig. 2*B*). At this stage the denticles on the sides below the first dorsal fin range from about 1.2 mm. to about 2 mm. in length.

At a slightly more advanced stage, as represented by a male of 690 mm., the smallest (i.e. the oldest) of the denticles on the trunk are tridentate (Fig. 2*C*), but many of the larger (i.e. younger) ones now have entire margins, though with pointed tips still, while denticles of intermediate sizes show various intermediate stages and the denticles on the body now overlap so regularly that they hide the skin.

Up to this stage the denticles vary considerably in size from one to the next, with those on the sides below the first dorsal fin ranging from about 1 mm. to about 2.4 mm. in length. But those on the adult female of 1035 mm. (Fig. 2*D*) are all about equal in size over any given region of the body. And they no longer include any tridentate forms except near the tips of the pectoral fins.

This seems an appropriate place to remind the reader that on adult *coelolepis* (females, at least; adult males have not been seen) the denticles are largest (about 3-3.5 mm. long) on the mid sector of the trunk, belly as well as sides and back, and are progressively smaller not only forward, but rearward as well, with those on the caudal peduncle on the average only about 70 per cent as long as those on the sides below the first dorsal fin.

The discovery that the denticles are of one shape on young specimens of this particular species of shark, but of a strikingly different shape on adults, opens vistas that are interesting from the standpoint of elasmobranch morphology in general, as well as from that of taxonomy.

To begin with, it poses the question, how long is the normal life span of a dermal denticle in relation to the life of the individual? So far as we can learn, no special attention has been paid to this point, nor is it safe to reach any conclusion *a priori* here, for while the teeth of sharks, which correspond in all essentials with the placoid scales or dermal denticles, are replaced periodically, the dorsal fin spines — equally homologous with the denticles — are retained throughout life in such sharks as have them. Among bony fishes, the general rule is that a scale, once formed, persists throughout the life of the fish, growing in size meantime, at a rate that keeps pace (more or less) with the rate of growth of the fish. In fact, the determination of the ages of fishes by the markings on their scales, a familiar procedure in fisheries biology nowadays, is based on belief in the validity of this rule. But Hertwig's (1874, p. 358) observation that new dermal denticles are formed between pre-existing ones in some sharks,[1] not only during embryonic development but during later life as well, shows that the situation is not so simple for elasmobranchs.

Counts of about twice as many denticles within a given percentage of the total length of a specimen, below the first dorsal fin, of *C. coelolepis* 565 mm., 690 mm., and 1035 mm. long as on an embryo of 277 mm. (for details, see p. 49) show that the final number is developed, in this particular species, by the time a given specimen is about half grown — how much earlier is not known. It also seems evident, from the shapes and relative sizes of the denticles, and from their irregular arrangement, that several generations of them are represented on small examples as illustrated by our specimens of 565 and 690 mm. (Fig. 2, *B*, *C*). But the uniformity in size and shape of the denticles on adults, and the regularity with which they are arranged, suggest that the ovoid ones that first develop on specimens a little more than half grown represent the final generation, which persists throughout the later life of the individual concerned. We can go no farther than this from information available up until this time.

We think it probable, too, that a similar succession in the shapes of the denticles takes place between young specimens and adults, in the case of *Centroscymnus owstoni* Garman 1906, from Japan, a near relative of the North Atlantic *C. coelolepis*. When adult, its denticles resemble those of adult *coelolepis* very closely in shape. But they are tridentate over the trunk as a whole on two

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[1] It is not clear, from the context, whether Hertwig made these particular observations on *Mustelus*, on *Acanthias*, on *Dalatias* or on *Heptranchias*.

Japanese squalids, 260 mm. and 287 mm. long, in the Museum of Comparative Zoology, which agree very closely in all other respects (including very minute denticles, very oblique lower teeth, and no median tooth in the lower jaw) with two adult males of *owstoni,* 785 mm. and 805 mm. long, in the Museum. Incidentally, the two small specimens just mentioned came from Japan labelled *Scymnodon squamulosus.* But they differ sharply from *squamulosus* as pictured by its describer (Günther, 1878, pl. 2, fig. B) both in their very oblique lower teeth, and in pectorals reaching back as far as the level of the origin of the first dorsal fin, for the lower teeth of *squamulosus* are shown as nearly erect, and the tips of its pectorals as falling short of the level of the origin of the first dorsal by a distance about as great as the length of the snout in front of the mouth.

On the other hand, the successional history of the denticles of *Centroscymnus coelolepis* strengthens the specific validity of *C. cryptacanthus* Regan 1906, from Madeira, the denticles on the type specimen of which (about 700 mm. long) were tridentate with 3 parallel keels on the trunk anterior to the first dorsal, but ''the others smooth, with rounded edges and with a rounded depression on the free surface of each'' (Regan, 1906, p. 437).

Present realization that it is not safe to define species of sharks by the shape of their denticles — unless the ages of the specimens in question be taken into account — forces us, next, to conclude that the juvenile squalids, 330-462 mm. long on which Bigelow, Schroeder and Springer (1953, p. 233) based the new species *Scymnodon melas* actually represent nothing more than an early stage in the growth of *Centroscymnus coelolepis.* Thus their denticles correspond very closely to the smallest and most tridentate of those of our 565 mm. *coelolepis* (p. 49, Fig. 2*B*), though they contrast so strongly with the rounded denticles of the adult that we would never have guessed that they belonged to the same genus, much less to the same species, had it not been proven that the denticles of the young of *coelolepis* are similarly tridentate, to be replaced by ovoid ones later. The somewhat wider spacing of the denticles on the supposed *melas* than on partly grown *coelolepis* points merely to an earlier stage in the growth of the individuals. Neither can we find any better excuse for retaining the species, whether in proportional dimensions, in the fins, or in the shapes and number of teeth. And while we had thought its black color distinctive, as contrasted with the chocolate hue of the adult *coelolepis,* embryos of the latter, of proven parentage, are a very deep blue, while half-grown males are black, with only a faint tinge of chocolate to forecast the color of the adult.

The previous records for this species for the western Atlantic have been scattered along the slope, from the Grand Banks of Newfoundland to the offing of Nantucket. It is therefore interesting — as it was unexpected — that the three caught by "Cap'n Bill II" were all taken between the offings of New York and Delaware Bay, as follows:

Length in mm.	Sex	Lat.	Long.	Depth in fathoms
1035	♀	38°41′N	73°01′W	570-610
690	♂	39°09′N	72°21′W	485-520
555	♂	38°43′N	72°56′W	630-675

Our failure to take *coelolepis* off Georges Bank, or off Nova Scotia, where it was reported so often by the halibut fishermen years ago (Bigelow and Schroeder, 1948a, p. 498), and where about 90 successful hauls were made in 1949, 1952 and 1953 at depths greater than 200 fathoms, including about 40 hauls deeper than 400 fathoms, is something we cannot explain.

Earlier captures of *coelolepis* in American waters were from depths of 150-250 fathoms — all of them made with hook and line. But we have already noted the likelihood that it would be found much farther down the slope in the western side of the ocean, as it is in the eastern, if fished for there with suitable gear. And the "Cap'n Bill II" trawlings bear out this expectation, by extending its known range in American waters down to 630 fathoms at least.

BATOIDS

Family RAJIDAE

Skates

RAJA BATHYPHILA Holt and Byrne 1908

The capture by "Cap'n Bill II" of a female *R. bathyphila,* 360 mm. long, on the seaward slope of Georges Bank (Lat. 40°04′N, Long. 68°34′W), at 370-450 fathoms in 1952, and of a juvenile male of 370 mm. at a neighboring station (Lat. 40°10′N, Long. 68°16′W) at 490 fathoms, added to earlier locality records for it at one station off Chesapeake Bay, at 3 stations off southern New England, and at one station off Browns Bank, in depths of 885 to 1188 fathoms,[1] show that this deep water skate is generally distributed along the mid zone of the continental slope, between the offings of Chesapeake Bay and of southern Nova Scotia. Knowledge as to its status farther to the northeastward along the American slope is to be desired to tell us how wide the gap may be between the geographic ranges occupied by it in the western side of the Atlantic, and in the eastern, where it is known only from the Irish slope (type specimen), so far as we are aware.

The depths of capture recorded for it so far (370-1188 fathoms on the American slope, 673 fathoms on the Irish) suggest that its center of population lies deeper than 400-500 fathoms, with the upper limit little shoaler, if at all, than 350 fathoms.

The most distinctive character of *bathyphila* is that its entire lower surface is darker than the upper surface. Indeed, it is unique in this respect, among the skates that are known from the North Atlantic outside of the Gulf of Mexico. Within the Gulf it is paralleled in this respect by the newly described *R. fuliginea* Bigelow and Schroeder 1954. But the latter differs from *bathyphila* so sharply in a more convex anterior outline as well as in the prickliness of the lower surface of its tail and of the upper sides of its pelvic fins that there is little likelihood that the one species could be taken for the other. For a comparison of *bathyphila* with the several skates of the Pacific and Indian Oceans that are similarly dark colored below, see Bigelow and Schroeder 1953, p. 161.

A character, almost equally diagnostic for *bathyphila* among skates of its geographic province, but one that has not been stressed previously, is the narrowness of its mouth. In the four specimens that we have measured[2] the breadth of the mouth ranges from 4.9 to 5.9 per cent as great as the total length. The only other skates known from the northwestern Atlantic, outside of the Gulf of Mexico, that approach it closely in this respect are *Raja garmani* Whitley 1939 (about 5.7-5.9 per cent); *R. fyllae*

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[1] For details, see Bigelow and Schroeder, 1953, p. 159.

[2] The two "Cap'n Bill II" specimens, and two others, the proportional dimensions of which are given in Bigelow and Schroeder 1953, p. 161.

Lütken 1887 (5.8 per cent in eastern Atlantic specimen, 6.1-7.0 per cent in four of the "Cap'n Bill II" specimens, 397-497 mm. long); and *Breviraja plutonia* (Garman) 1881 (5.1, 5.6 per cent, in two specimens taken off Jacksonville, Florida). And there is no likelihood of confusing *bathyphila* with any of these, quite apart from its coloration. Thus the anterior contour of the disc of *bathyphila*, half-grown and larger, differs widely from that of *fyllae*, and the arrangement of thorns and prickles is noticeably different in the two species, as we have pointed out elsewhere (1953, p. 159). The plain coloration of the upper surface of *bathyphila* contrasts as strikingly with the pattern of dark rosettes on *garmani* as does the dark lower surface of *bathyphila* with the pale lower surface of *garmani*. And no one, we fancy, would be likely to mistake a *bathyphila*, wedge shaped in front, with tail only moderately long, and a hard snout, for a *plutonia*, with its much more convex anterior outline, much longer tail and soft snout.

The male *bathyphila* taken in 1953 has six large thorns along the mid line of the back from the scapular region to the level of the axils of the pectorals, with the single median row reaching back as far as the axils of the pelvics; the female has seven large medians between scapular region and level of axils of pelvics, rearward from which there are 2-3 less regular rows. Thus these specimens, 370 and 360 mm. long, respectively, represent a stage in development between the 463 mm. female pictured by us in Part 2 of Fishes of the Western North Atlantic and the somewhat smaller (323 mm.) male (1953, Figs. 30, 31A). They agree so closely with our earlier account of this species in all other respects that no further discussion of them seems needful from the taxonomic standpoint.

RAJA FYLLAE Lütken 1887

This skate was included in our general survey of the rajids of the western North Atlantic (Bigelow and Schroeder, 1953, p. 194) because of its presence in west Greenland waters, where it has been known for many years, as it has in boreal and subarctic latitudes in the eastern side of the Atlantic. The cruises of "Cap'n Bill II" have now extended the known range of *fyllae* to the Nova Scotian slope, and even to the southwestern slope of

Georges Bank, in depths of 290-600 fathoms. It must, indeed, be very generally distributed (though in small numbers) along this depth zone between the offing of Halifax and the seaward slope of Browns Bank (longitudes 63°47′W to 65°06′W) for it was taken in 8 of the 19 successful hauls that were made there in 1952 (16 specimens) as well as in 8 of the 16 successful hauls made there in 1953 (13 specimens). And we may expect it to prove equally widespread around the Newfoundland Banks when the 300-600 fathom depth zone has been explored there more fully. But it seems to be much less numerous farther to the westward — unless at a considerably greater depth — for only

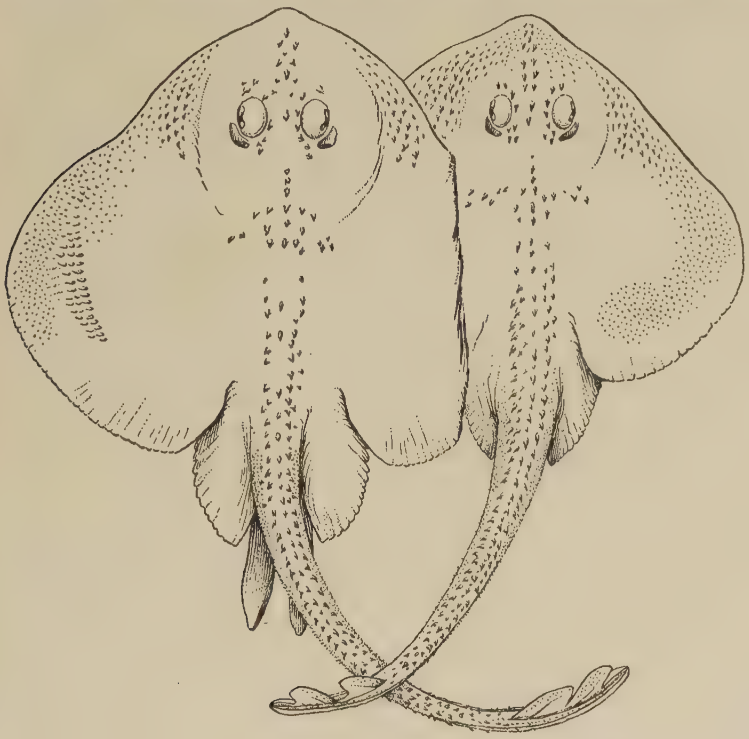

Fig. 3. *Raja fyllae. Left,* male, 505 mm. long, off La Have Bank, M.C.Z. No. 37905; and *right,* female, 430 mm. long, same general locality, M.C.Z. No. 37898.

three hauls (3 specimens) yielded it on the Georges Bank slope (longitudes 67°02′W to 68°54′W), out of the 24 successful hauls that were made in 1952 and 1953, combined, at depths greater than 300 fathoms, between longitudes 66°W and 70°W. And it was not taken at all in the many hauls made farther to the westward and southward.

The Nova Scotian-Georges slope specimens (Fig. 3) agree so closely with the specimen from southwest of Ireland, figured by us (Bigelow and Schroeder, 1953, Fig. 39), both in shape of disc, in proportional dimensions including length of tail, and in dermal armature, that no cleavage is apparent between the populations inhabiting North American and north European waters. But the additional material allows us to expand our earlier description of the species in the following particulars.

A — Length of tail. In 7 of the larger specimens, 407-505 mm. long, including 2 mature males, the tail, measured from the center of the cloaca, occupies 58-61 per cent of the total length, and the ratio between length of tail and length of body is between 1.35 and 1.56. In 5 juveniles of both sexes, 198-272 mm., this ratio is 1.69-1.80. In *R. erinacea* and in *R. ocellata* (only skates with which *fyllae* might be confused in American waters) the ratio, length of tail to length of body, is about 1.00-1.35.

B — Shape of disc. The anterior contour of an adult male 505 mm. long, in the "Cap'n Bill II" series (Fig. 3) parallels closely that of a somewhat larger male (555 mm. long) from West Greenland that was pictured first by Lütken (1898, Pl. 2), and subsequently by Clark (1926, Pl. 22, fig. a) in being deeply concave on each side, abreast of the spiracles, a point worth mentioning since these are the largest males that have yet been seen, so far as we are aware. Females from off Nova Scotia, 397 and 430 mm. long, agree very closely in the shape of their discs with a female of 452 mm. taken southwest of Ireland that we have pictured elsewhere (Bigelow and Schroeder, 1953, p. 195, Fig. 39).

Students of skates have learned, long since, to expect considerable variation in dermal armature from specimen to specimen in nearly every species, both for the larger thorns and for the smaller prickles as well, though each species shows a basic arrangement that is characteristic of it. Our predecessors have observed, already, that *fyllae* is no exception to this rule; and the Nova Scotian specimens afford an additional illustration. Thus the areas bare of prickles that tend to develop on the upper surface of its disc, as this skate grows, vary considerably in their extent among the females, independently of the sizes of the latter. In one, 430 mm. long, there is a bare area behind each spiracle, reaching rearward to the shoulder region, and there are no prickles on the upper surface of the pelvics. But the regions rearward from the spiracles are prickly on another female of 397 mm., and also the upper surface of the posterior lobe of each pelvic fin, much as they are on a female of about this same size taken off Ireland (Bigelow and Schroeder, 1953, Fig. 39), and in all of the smaller specimens of both sexes taken off Nova Scotia.

The males, as they mature, tend to lose any prickles they may have had earlier on the pelvics, and also to lose part of the larger thorns from the mid-dorsal belt of the disc between the levels of the pectoral girdle and of the axils of the pectorals.

It was known, previously, that the upper surface of the tail, which is set with prickles (besides the thorns) on small specimens, loses most of these prickles with growth. It now seems that this alteration is a more regular one than previous observations had suggested, for while the tail is uniformly and densely prickly above on the Nova Scotian juveniles, to 270 mm. long, it is wholly bare of prickles along a definite median band throughout its length back to the first dorsal fin on the larger Nova Scotian specimens of 397-505 mm. The shape, too, of the tail alters in *fyllae* with growth, from arched above in the young to flat above in adults, along the median band that has become bare of prickles.

A feature which seems to have escaped scientific attention is that the mucous pores on the nuchal region of *fyllae* are arranged in a pattern that is conspicuous on small specimens as well as on large. The only other skate of the western North Atlantic in which the pores in this region are noticeable is *R. laevis*, but they are black pigmented in the latter, whereas they are pale in *fyllae*.

Thirty to thirty-eight series of teeth have been recorded for *fyllae*. In the larger of the Nova Scotian specimens, 397-505 mm. long, the number of series varies more widely in the upper jaw (30-38) than in the lower jaw (30-32). It is not known whether this same disparity obtains for the European population of this species.

The northeastern Atlantic and west Greenland representatives of *fyllae* so far seen have been ashy gray to chocolate brown above, the adults uniform, the young marked more or less distinctly with darker spots. One of the larger of the Nova Scotian females 430 mm. long, and 2 others half to three-quarters grown, are similarly of a uniform ashy gray tint above. But 5 other females are conspicuously marked, above, with an oblong whitish blotch, longer than wide, between the eyes, and with a similar but vaguely outlined pale blotch on the inner posterior part of each pectoral fin, a pattern of which we find no previous report for *fyllae*. One large male and 1 half grown lack these blotches but 1 large and 2 half to three-quarters grown males are so marked for *R. fyllae*. The lower surface is uniformly grayish white on the largest Nova Scotian male (505 mm.) both on tail and on disc. But the lower surface of other large specimens is more or less smoky around the outer posterior edges of the pectorals, in the region of the cloaca, and on the anterior parts of the pelvics; their tails are variously dark-blotched or mottled below; the region of the gill openings is smoky on one of them; and there is a smoky prepelvic blotch on three of them. Thus the dark markings on the lower surface vary as widely from specimen to specimen in extent and in arrangement among the Nova Scotian population as among the Greenland and eastern Atlantic populations.

The fact that the claspers are small, still, on one "Cap'n Bill II" male of 442 mm., but seem ready to function on another of 505 mm., on which the alar thorns have also developed in 2-3 rows, suggests that males of the Nova Scotian population mature, sexually, at a length of perhaps 475-500 mm.

The only other western North Atlantic skates that *fyllae* resembles closely in shape of disc, and in the general arrangement of its dermal armature, are *R. erinacea* Mitchill 1825, and *R. ocellata* Mitchill 1815. We have pointed out already (1953, p. 196) that it differs from both of these in a longer tail. But the measurements of the *fyllae* that we now have at hand show that the distance from the axils of the pelvics to the first dorsal fin as employed in our key (1953, p. 150) is not as reliable a criterion as it seemed. Thus, while this distance is greater than from axils of pelvics to fronts of orbits in most of our *fyllae*, it is only about as great as to the mid levels of the orbits in a few, and is somewhat shorter than to the rear edge of the orbits in one adult male,[1] as it is in *erinacea* and *ocellata* also. And while the total length of the tail (measured from center of cloaca) is the greater relative to the length of the body in *fyllae*, there is virtually no discontinuity in this respect, as appears from the following table.

Ratio, total length of tail (from center of cloaca) to length of body

	max.	min.	average	number of specimens	total lengths mm.
fyllae	1.80	1.35	1.57	12	198—505
erinacea	1.35	1.06	1.22	9	209—505
ocellata	1.10	0.97	1.05	4	414—809

The distance, however, from the origin of the first dorsal fin to the center of cloaca is longer than from the cloaca to the tip of the snout in all the specimens of *fyllae* that we have measured, but shorter than from cloaca to snout both in *erinacea* and in *ocellata*, as follows:

Ratio, distance from first dorsal to cloaca relative to distance, cloaca to tip of snout

	max.	min.	average	number of specimens	total lengths mm.
fyllae	1.36	1.03	1.19	10	202—505
erinacea	0.97	0.81	0.88	5	209—505
ocellata	0.79	0.71	0.74	5	423—641

The interorbital space is narrower on *fyllae*, averaging 6.73 per cent (6.12-7.30) of the width of disc on 13 specimens examined, than it is on *erinacea* with an average of 8.01 per cent (7.32-8.50) on 11 specimens, or *ocellata* with an average of 9.12 per cent (8.82-9.32) on 4 specimens.

For specimens that cannot be identified, positively, by length of tail alone, the teeth should usually prove diagnostic, for there are only 30 to 38 series in the upper jaw in *fyllae* contrasted with

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[1] Abnormal?

38 to 64 in *erinacea,* and 72 to 110 in *ocellata.* And the arrangement of the thorns on the tail usually is distinctive for large specimens, and in most cases for half grown, for *ocellata* and *erinacea* of these sizes usually have a narrow naked band along the mid line which has not been the case in any *fyllae* we have seen. But we must admit that specimens might come to hand for which depth of capture would be the only reliable criterion for identification that we have been able to discover.

In any case there is little danger of confusing *fyllae* either with *erinacea* or with *ocellata* in the field, for it has never been taken in North American waters shoaler than 290 fathoms, and neither of the others deeper than 85-87 fathoms (two *erinacea* trawled by "Cap'n Bill II" off the southern edge of Georges Bank in July 1953).

RAJA JENSENI Bigelow and Schroeder 1950

The captures of a female *jenseni,* 625 mm. long and in good condition, by "Cap'n Bill II" on the slope of Browns Bank, Lat. 42°19′N, Long. 64°59′W, in a trawl haul at 390-440 fathoms, and of a second female, of 695 mm., off Delaware Bay (Lat. 38°47′N, Long. 72°54′W) at 585-595 fathoms, call for mention, for the only specimens of this deep water skate that had been reported previously were a male, of 223 mm. from the slope of Georges Bank, 1255 fathoms; a female (the type) of 541 mm. off southern New England, 1043 fathoms; and a female of 850 mm. (now fragmentary) from off Halifax, Nova Scotia, brought in by a fisherman from 200 fathoms;[1] all are now in the U. S. National Museum, and all were taken many years ago.

The "Cap'n Bill II" specimens agree so closely with the type specimen (Bigelow and Schroeder, 1950, Pl. 1; 1953, Fig. 45) that their specific identity is evident at a glance. There are 29 large thorns in the mid dorsal row on the 625 mm. female, 8 of them anterior to the level of the axils of the pectorals. On the 695 mm. specimen, the total number in the median row is 26, 6 of which are anterior to the level of the axils of the pectorals, so spaced as to suggest that 3 or 4 others had been lost. These counts contrast with a total of 24 or 25 on the type (7 anterior to the axils of the pectorals) and with a total of 31 on the smaller male (8 anterior to the axils of the pectorals). Evidently there is a small variation in number from specimen to specimen, independent of the sizes of the latter. Enough specimens have been seen to show that it is characteristic of *jenseni* for the mid-dorsal thorns to be widely spaced anterior to the pelvic girdle, but increasingly closely spaced thence rearward onto the tail. On the 625 mm. female the thorns on the disc are about 20 mm. apart; those abreast of the axils of the pelvics about 10 mm. apart. The next 8 thorns along the tail are in contact at their bases, but the thorns thence rearward are separated, one from the next, by short interspaces. Also, the thorns are successively smaller, rearward along the posterior third of the tail. As on the type, there is no thorn in the interspace between the two dorsal fins on either of the ''Cap'n Bill II'' specimens, but only a few prickles.

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[1] For the nomenclatural history of *jenseni,* description, and illustrations, see Bigelow and Schroeder, 1950, p. 385, Pl. 1; 1953, p. 213. Figs. 45, 46.

The presence, on each side, of 3 or 4 thorns on the scapular region on the small male of 223 mm., and of 3 on the type, 541 mm. long, but of 2, only, on both of the ''Cap'n Bill II'' specimens of 625 mm. and 695 mm. indicates that one or two of the thorns in this group are lost with growth. There may be either two postocular thorns or three on different specimens,[1] but every specimen that has been seen has had one preocular thorn, only, on each side. The tip of the snout and the rostral ridge are about as rough on the ''Cap'n Bill II'' specimens as on the type, and the small prickles are about as densely distributed and cover about the same areas. A point worth emphasis is that while the sides of the tail of *jenseni* are densely prickly there are no prickles on the lower surface of its tail below the level of the lateral folds. The lower surface of the disc is naked everywhere.

Fifty-eight and sixty-six series of upper teeth have been reported previously, for the two specimens for which they have been counted. The ''Cap'n Bill II'' female 625 mm. long has 60, but the 695 mm. specimen has only 51. Evidently the number is widely variable on this species, irrespective of size, much as in *R. erinacea,* and in *R. ocellata.* The teeth resemble those of the type specimen closely (Bigelow and Schroeder, 1953, Fig. 46D) both in shape and in arrangement.

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[1] Three on the 850 mm. female; two on each of the other specimens that have been examined.

We have forecast already that the dark markings on the lower surface of the disc, in *jenseni*, would prove widely variable (Bigelow and Shroeder, 1953, p. 216), and the "Cap'n Bill II" specimens corroborate this expectation. The ground-tint in both cases is yellowish white. On the 625 mm. specimen this is clouded with ashy gray around the posterior marginal zone of the pectorals and on the outer posterior parts of the pelvics; in the region of the cloaca and forward on either side of the abdomen; also over an irregular area on each side close behind the mouth. On the 695 mm. female the lower surfaces of the pelvics, the abdominal region in general, the lower surfaces of the pectorals, an irregular area on either side inward and forward from the gill region, and another smaller, inward from the nostril, are dark sooty gray. This pattern simulates, rather closely, the dark markings on some specimens of *R. hyperborea* (Bigelow and Schroeder, 1953, p. 209, Fig. 44), from which *jenseni* differs quite sharply by having a more simple dermal armature and fewer teeth (Bigelow and Schroeder, 1953, p. 213). The lower surface of the tail has been plain dark ashy gray on all the specimens of *jenseni* that have been seen thus far.

The localities whence *jenseni* has been reported (see above) are scattered sufficiently to show that it is generally distributed along the upper part of the slope between the offings of middle Nova Scotia and of Delaware Bay. But we have yet to learn how much farther its geographic range may extend in either direction. And the paucity of captures, with the great depths at which the "Albatross" specimens were taken, suggests that while a sparse population exists as shoal as 200-600 fathoms, the center of abundance for this species lies deeper down the slope than has been sampled yet by adequate methods of fishing.

RAJA LAEVIS Mitchill 1817

Barn Door Skate

This skate has been recorded as deep as 235 fathoms, but it occurs most regularly, and in greatest numbers on the continental shelf in depths shoaler than 70-80 fathoms. Hence captures of it by "Cap'n Bill II" at 265-305 fathoms off Nova Scotia (2 specimens in 2 hauls, Lat. 42°23′—42°28′N; Long. 64°31′—

64°52′W), and at 300-410 fathoms off Nantucket (1 specimen in 1 haul, Lat. 39°54′N, Long. 69°56′W) are of interest, as extending the known depth-range of the species downward, somewhat.

Other records of it, from the trawlings of 1952 and 1953 were from 220-255 fathoms on the seaward slope of Georges Bank (1 specimen, Lat. 40°11′N, Long. 68°20′W), and from 175-225 fathoms off southern New England (1 specimen, Lat. 40°04′N, Long. 72°12′W, 190-225 fathoms, and 2 specimens in 1 haul, Lat. 39°56′N, Long. 71°22′W, 175-200 fathoms).

RAJA MOLLIS Bigelow and Schroeder 1950

The type—and only known—specimen of this species, trawled on the slope off southern Nova Scotia, Lat. 41°53′N, Long. 65°35′W, at a depth of 858 fathoms by the "Albatross" in 1883, had rested, unnoticed, in the U. S. National Museum until 1950. We can now add three more records for *mollis* from that same general region, namely, a juvenile male, in the neighborhood of 195 mm. long (tip of tail lost) taken by the "Caryn" in June 1949, at Lat. 41°25′N, Long. 65°54′W, in a trawl fishing between 415 and 490 fathoms; a second male, of 267 mm. taken by "Cap'n Bill II," July 26, 1952, at Lat. 42°40′N, Long. 63°51′W, from 465-480 fathoms; and a third, 298 mm. long, July 12, 1953, from Lat. 42°40′N, Long. 63°52′W, at 415-420 fathoms.

The fact that "Caryn" and "Cap'n Bill II" took only three specimens of *mollis* in the 39 hauls they made at depths deeper than 300 fathoms in the Nova Scotian sector during the three summers combined, coupled with the depth (850 fathoms) at which the type specimen was trawled, makes it likely that the center of population for this species is along the lower part of the continental slope. But it is anyone's guess how far its geographic range may extend, either to the northeastward, or to the southwestward.

Mollis falls in the moderately short-tailed subdivision of the genus, the distance from the level of the axils of its pelvics to the first dorsal fin being much shorter than from the axils of the pelvics to the tip of the snout, and the total length of its tail from the cloaca being only about 1.1 times as long as the body from center of cloaca to tip of snout. Its most noticeable external characteristics are that it has no large thorns anywhere, posterior to the scapular region, but that the upper surface of its disc and tail are densely prickly, except close along the outer posterior edges of the pectorals, and that the entire breadth of the lower surface of its tail is also densely prickly, except for the extreme tip.[1] The only slight differences worthy of mention between the larger of the two "Cap'n Bill II" specimens and the type is that the former has two minute thorns close in front of each eye (only one in front of each eye on the type); and that while there is a very small postocular thorn (as on the type) on one side of its head, none is to be seen on the other side among the close-set prickles that roughen the skin there. There are 54 series of teeth in the upper jaw of the "Caryn" specimen about 195 mm. long, 60 in both the "Cap'n Bill II" specimens of 267 and 298 mm., and 60 on the type specimen.

On the type specimen, the rostral projection from the cranium, reaching nearly to the tip of the snout (easily felt) is soft throughout its length. It is soft on the "Cap'n Bill II" specimens also and this state is so unusual, among the members of the genera *Raja* and *Breviraja*, that we considered it as perhaps the outstanding feature of the species *mollis*, in our earlier discussion (1953, p. 237). But the rostral cartilage of the very small specimen (195 mm. long) collected by "Caryn" in 1949 is rather stiff to the touch, raising the question as to whether its degree of firmness is a matter of the stage in growth, or whether it perhaps is affected by preservation.

RAJA RADIATA Donovan 1807
Thorny Skate

Previous knowledge of the range of the thorny skate, and the numbers in which it has been taken on the Newfoundland Banks, in the inner parts of the Gulf of Maine, and on Georges Bank (Bigelow and Schroeder, 1953, p. 262) had led us to expect a plentiful representation of this species among the catches that were made off Nova Scotia, and along the seaward edge and slope of Georges Bank by the "Cap'n Bill II" in 1952 and 1953. But the results proved otherwise for it was taken in 10 hauls, only, in these two sectors combined, out of a total of 51 hauls that fished successfully there between 120 fathoms and 400 fathoms and none was caught in 34 deeper hauls. The total number of specimens, too, was only 12, the maximum catch in one haul only 2. This, contrasted with the large catches that have been made on the Newfoundland Banks, on Georges, and in the western side of the Gulf of Maine (Bigelow and Schroeder, 1953, p. 262) is evidence that while it has been taken as deep as 430-490 fathoms off New York by "Cap'n Bill II" (Lat. 39°26′N, Long. 72°12′W, July 1953) and at 459 fathoms near Spitzbergen, its center of abundance lies shoaler than the zone along which the great majority of the "Cap'n Bill II" hauls were made. But the sizes of the specimens taken at different depths make it likely that the thorny skate reproduces itself, indifferently, down to the greatest depth to which it occurs, for those taken shoaler than 300 fathoms ranged from 196 mm. to about 860 mm. in length, those taken deeper, from 145 mm. to about 865 mm. And while one from 240-270 fathoms contained an egg about ready for deposition, another from 400-460 fathoms contained a mass of immature eggs.

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[1] For detailed comparison with other species of *Raja*, see our earlier account (1953, p. 237).

This skate was taken at 8 stations out of 44 along the 120-400 fathom depth zone off southern New England in the two years combined; but, again, the largest catch was only 2 specimens, the total catch 11 and only 1 was caught in 26 stations deeper than 400 fathoms. Five specimens, also, were taken in 3 hauls fishing between 253 and 490 fathoms off Long Island, New York (longitudes 72°12′-72°19′) in June-July 1953 (it had been reported nearer land there, previously). But it seems that the so-called "Hudson Trough" off New York about marks the boundary to its regular occurrence in that direction at any depth, for "Cap'n Bill II" did not take it in any of the hauls that she made southward thence to the offing of Virginia in the summer of 1953, though we have seen a specimen from 74 fathoms off Charleston, South Carolina (Bigelow and Schroeder, 1953, p. 263).

RAJA SENTA Garman 1885

This skate, ranging from the Newfoundland Banks and the inner part of the Gulf of St. Lawrence to the offing of South Carolina, was already known to occur widespread, though in small numbers, from the offing of western Nova Scotia to the offing of

New Jersey; chiefly between 50 fathoms and 250 fathoms, but recorded as deep as 478 fathoms off South Carolina. Therefore, it was no surprise to take 1-2 specimens in each of 6 hauls at 125-340 fathoms along the slope of Georges Bank (Long. 66°51′W and 69°43′W), 1 or 2 in each of 7 hauls at 150-225 fathoms off southern New England (Long. 70°-72°01′W), 1 off Maryland (Lat. 38°38′N, Long. 73°10′W), at 190-200 fathoms, and 1 off Virginia (Lat. 37°38′N, Long. 74°14′W) in 1952 and 1953. The series ranges from 120 mm. in length to about 577 mm.; the largest is a male with well developed claspers.

Raja spinicauda Jensen 1914

Definite locality records for this cold-water skate had been limited, previously, to Barents Sea, to the waters east of Iceland, to southwestern Greenland and the Greenland side of Davis Strait, to the continental slope off eastern Newfoundland, and to Hermitage Bay on the southern Newfoundland coast. But the fact that an egg case, apparently of this species to judge from its external sculpture and from the embryo contained within it, had been brought in from Banquereau Bank, and that a similar case (empty) had been trawled on the southwestern slope of Georges Bank,[1] had made it likely that the range of *spinicauda* extended southward and westward along the upper part of the continental slope as far as the general offing of Cape Cod. And this likelihood has now been corroborated by the capture of a juvenile male 392 mm. long by "Cap'n Bill II" on the slope of Georges Bank (Lat. 42°17′N, Long. 65°06′W) at 320-360 fathoms, besides two egg cases (one with identifiable embryo) off southern Nova Scotia (Lat. 42°44′N, Long. 63°17′W, 410-420 fathoms) in 1952, and of a third egg case, with well advanced embryo, on the slope of Georges (Lat. 40°43′N, Long. 66°42′W, 405-430 fathoms) in 1953.

Spinicauda had been recorded previously from 77-88 fathoms (140-160 meters) off Iceland, 120-404 fathoms off west Greenland, and 120-140 fathoms in Newfoundland waters. The depths recorded for the partly grown male taken by "Cap'n Bill II" in 1952 (320-360 fathoms), as well as for the egg cases taken by "Caryn" in 1949 (260-350 fathoms) and by the "Cap'n Bill II" in 1952 and 1953 (405-430 fathoms) suggest that *spinicauda* occupies a somewhat deeper zone in the southernmost part of its range than in the northern part.

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[1] See Jensen (1948, pp. 50-52, and 53, Fig. 3) for records for Barents Sea, Iceland and Greenland; Bigelow and Schroeder (1953, p. 272, 276) for those for American waters.

The bottom temperature was 3.3° in 1953, at the only locality where *spinicauda* was taken (egg case with embryo) that summer, and 3.9°-4.4° along the general depth zone where either free-living *spinicauda*, or its egg case, was taken in 1949 or in 1952, years when the temperature was not recorded. These values suggest that the upper limit to its thermal range may be slightly higher off Georges Bank and off Nova Scotia than off the east coast of Newfoundland, where the bottom water, at the depth where it was taken (91-127 fathoms) was between –1.5° and +0.65°, or in west Greenland and Icelandic waters where it has been found in temperatures of 1.7° to 3.8°.

Spinicauda is given so distinctive an aspect by its wedge shaped anterior contour with very long snout, and by a generally prickly upper surface, but with larger thorns confined to a single row of 21-26 (three examined by us had 22, 23 and 24 thorns, respectively) along the mid line of the tail with one between the first and second dorsal fins, that it could hardly be mistaken for any other skate known from the western North Atlantic. The only noticeable respect in which our juvenile male differs from the adult is in a somewhat longer tail, a growth feature that also is known for several other skates. More in detail, the distance from the center of the cloaca to the first dorsal fin, relative to the distance from center of cloaca to tip of snout, is about 1.2 times as great on the "Cap'n Bill II" juvenile male, as on the mature male, 1,236 mm. long, from Newfoundland, the proportional dimensions of which are given in Part 2 of "The Fishes of the Western North Atlantic" (Bigelow and Schroeder, 1953, p. 272). And this divergence between small specimens and large is about what might have been expected; the corresponding ratio, for example, in length of tail between young and adult (measured similarly) is about 1.2-1.3 for *R. erinacea;* about 1.2 for *R. fyllae;* about 1.1 for *R. laevis;* 1.1-1.3 for *R. radiata;* and 1.1-1.3 for *R. senta.*

In the adult *spinicauda* the rostral projection from the front of the cranium (reaching very nearly to the tip of the snout) is slender and rodlike along the anterior ¾ of its length, and its cartilaginous nature is evident, if the skin above it be slit, and its sheath of fibrous tissue be spread apart. It is of the same shape in our juvenile male. But in this case the histologic nature of its anterior part remains to be learned, for it is only close to the cranium that it is visible on an X-ray photograph. And we have not felt free to dissect the single specimen, or to treat it with a stain selective for cartilage.

Ishiyama (1952, p. 2) has already pointed out that X-rays must be used with caution as tests for cartilaginous skeletal elements in rajids. We have found, for example, that while the outlines of the cranium, of the jaw cartilages, of the vertebral column, and of the basal cartilages of the paired fins show clearly in our X-rays of various skates and rays, those of the pectoral fins may, or may not. Thus, the pectoral radialia are sharply outlined on our X-rays of *Gymnura,* but the only visible evidence of them on X-rays we have studied of various species of *Raja, Breviraja, Cruriraja, Psammobatis* and *Sympterygia* is along the narrow axial strands of calcification. Consequently, X-ray photographs can be relied on as tests for the length of the rostral cartilage only if they show its anterior termination sharply.[1]

The egg cases trawled by "Cap'n Bill II" in 1952 and 1953 — identity established by the embryos contained in them — resemble those referred provisionally to this species by Jensen (1914, p. 33; 1948, pp. 55, 56) and by us (1953, p. 272) very closely. They are unique so far as known, among the egg cases of Atlantic skates, in the sculpture of their surfaces with a large number of low, longitudinal ridges, each close-set with a single series of several hundred stiff rod-like structures with complexly dissected tips (Fig. 4).

The three egg cases we have examined measure about 90 by 130 mm.; about 92 by 135 mm.; and about 86 by 136 mm., not counting the terminal horns. The embryo that one of them contained, 185 mm. long to its first dorsal fin, and 242 mm. to the tip of its tail, still bears the large yolk sac. But it is so nearly ready for birth that its identity as *spinicauda* is obvious. Embryonic characters — still persisting — apart from the yolk sac are that only the tips of the single line of caudal thorns (22 in number) show through the skin; that the length of the tail, from center of cloaca to first dorsal fin, relative to the distance from center of cloaca to snout, is about 1.2 times as great as in the

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[1] See, for example, Bigelow and Schroeder, 1948, Figs. 1, 2; 1953, Fig. 62.

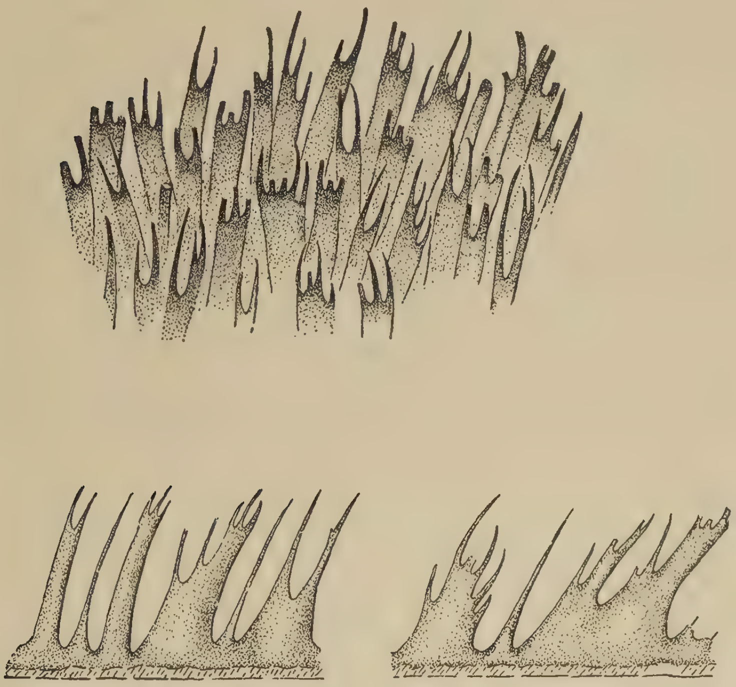

Fig. 4. *Raja spinicauda.* Portion of egg case trawled on the Nova Scotian slope in 410-420 fathoms, Lat. 42°44′N, Long. 63°17′W, M.C.Z. No. 37691, to show sculpture; above, about 7 x, below, about 11 x.

juvenile male of 390 mm.; that the tip of the tail still carries the embryonic filament which with the caudal fin fold extends 35 mm. from the rear base of the second dorsal; and that the thorn is not yet visible between the two dorsal fins.

CHIMAEROIDS

Family CHIMAERIDAE

Hydrolagus affinis (Brito-Capello) 1867
Deep Water Chimaera

This chimaera was described originally from deep water off Portugal. The first report of it, on our side of the Atlantic, was by Gill in 1878 (as *Chimaera plumbea* n. sp.), from one brought in from 350 fathoms off La Have Bank. So many of them were brought in during the next few years, by schooners long-lining for halibut, that Goode and Bean (1895, p. 31) characterized it eighteen years later as "very common in the deep water on the outer edge of the banks north of Georges Banks."[1] And while one specimen, only, is known to have been taken on the American slope during the past quarter century, we have risked the prediction that "it would be found on the offshore slopes in undiminished numbers if it were sought at the proper depth" (Bigelow and Schroeder, 1953, p. 544). This, then, was one of the fishes we expected the trawlings of "Caryn" and of "Cap'n Bill II" to yield. But they did not catch a single specimen. The failure to take this particular species can hardly be blamed on insufficient coverage of the zone explored, for 38 successful hauls reaching deeper than 200 fathoms were made along the slope of Georges Bank, 26 of which fished deeper than 300 fathoms, 19 deeper than 400 fathoms and 3 deeper than 500 fathoms; 49 hauls reaching deeper than 200 fathoms along the Nova Scotian slope, 39 of them deeper than 300 fathoms; 21 deeper than 400 fathoms and 7 hauls deeper than 500 fathoms, in the summers of 1949, 1952, and 1953 combined.

The fact that all reports of *affinis*, for the western side of the Atlantic, have been based on specimens caught with hook and line might suggest that our method of fishing was at fault. But the otter trawl is so efficient an apparatus that we think it more likely that *affinis* actually is far less numerous along the Georges Bank and Nova Scotian slopes today than it was, there, 50-70 years ago.

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[1] For reports of it, in the Western Atlantic previous to 1953, see Bigelow and Schroeder, 1953, p. 544.

Family RHINOCHIMAERIDAE

RHINOCHIMAERA and HARRIOTTA

The most striking feature of these bizarre chimaeroids is their very long pointed snout, supported chiefly by the correspondingly long upper rostral cartilage. This cartilage follows the same course in *Harriotta* as is pictured for it in *Rhinochimaera* by Garman (1904, Pl. 1, fig. 2) and by Dean (1904, Pl. 1, fig. 4). We may add to our earlier account (1953, p. 549) that it is separated from the skin along the inner part of the snout by a mass of white, semigelatinous, pulpy tissue. The cartilage is in close contact with the overlying skin toward the tip of the snout for a short distance in *Rhinochimaera* of both sexes, also in females and young males of *Harriotta*, and for a longer distance in mature males of the latter, the tips of the snouts of which are hard. The cartilage as we have pointed out (1953, p. 549) is more flexible in the vertical plane around the crest of its curvature than elsewhere, so that it is easily bent down there mechanically, even on preserved specimens. But we have yet to learn whether the fish can direct the outer part of the snout upward or downward voluntarily.

Three genera of rhinochimaerids are known: *Neoharriotta* Bigelow and Schroeder 1950, type species *N. pinnata* (Schnakenbeck) 1929[1] (West Africa south of the equator), with separate anal fin; *Harriotta* Goode and Bean 1895 (North Atlantic, Japan, and off lower California) and *Rhinochimaera* Garman 1901 (North Atlantic and Japan), without separate anal. Characters that we have accepted previously (1953, p. 549) as alternative between *Harriotta* and *Rhinochimaera* are the nature of the dental plates (smooth in *Rhinochimaera* but with grinding ridges and knobs in *Harriotta*), and whether the upper margin of the caudal fin is smooth (*Harriotta*) or is armed with a longitudinal row of denticulate structures (*Rhinochimaera*). Examination of the representatives of each that were taken during the recent trawling trips of "Caryn" and of "Cap'n Bill II" shows that the first of these criteria can be relied upon, except for newly hatched specimens, the dental plates of which are smooth, or very nearly so in *Harriotta* as well as in *Rhinochimaera*. In fact we have found no reliable feature to separate newly hatched specimens of the North Atlantic representatives of *Harriotta* and of *Rhinochimaera* generically, though it is easy to do so specifically. It proves, also, that the presence of denticulations along the upper side of the caudal fin is reliable as a distinctive criterion for adult males of *Rhinochimaera*, as contrasted with *Harriotta*, but not for young males, or for females, as is pointed out below (p. 80). And it must remain an open question, until growth series of *Rhinochimaera* can be studied, as to how early these denticulations develop. All we can say, in this regard, is that while the upper margin of the caudal is so thick and fleshy in adult *Rhinochimaera* of both sexes that the horny rays are entirely concealed, it is so thin on a female *R. atlantica* 457 mm. long that these rays are clearly visible. The development, also, of a double series of hard knobs along the terminal ⅕-¼ of the snout of maturing males in *Harriotta raleighana* and in its close relative *H. chaetirhamphus* (Tanaka) 1909, of Japan,[1] but not in *Rhinochimaera* seems more properly a generic character than a specific. Another character, not proposed previously as alternative, between *Harriotta* and *Rhinochimaera*, but which seems to be so, is the shape of the outer part of the long upper rostral cartilage which is subtriangular (base uppermost) in cross section in *Harriotta* but is nearly as thick along its lower side as along its upper side in *Rhinochimaera*.

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[1] Given erroneously as 1931 in Bigelow and Schroeder 1953, p. 550.

RHINOCHIMAERA ATLANTICA Holt and Byrne 1909

This chimaeroid, previously known from the type specimen only, from the Irish Atlantic slope, and from a few empty egg cases presumably referable to it, was represented by 8 specimens in the "Cap'n Bill II" collections. These range from a newly hatched male, 151 mm. in total length, to large adults of both sexes 1060-1315 mm. long. According to Holt and Byrne (1910, p. 19, Pl. 3) *atlantica* differs from *pacifica* (Mitsukuri) 1895, of Japan, in a relatively shorter second dorsal fin, which they picture as shorter than the distance from the gill openings to the origins of the pelvic fins, but which they characterize as longer than that distance in *pacifica*, as it is shown on Dean's (1904, Pl. 1, fig. 1) illustration. But the second dorsal of *pacifica* is shown as only about as long as from gill opening to pelvic origin by Mitsukuri (1895, Pl. 1), and as shorter than that distance by Garman (1904, Pl. 1, fig. 1). The ratios, tabulated below, between length of base of second dorsal and distance from gill opening to pelvics, for the "Cap'n Bill II" series of *atlantica*, and for two specimens of *pacifica* in the Museum of Comparative Zoology (one of these was the basis of Garman's illustration) are further evidence that the Atlantic population cannot be separated from the Japanese on this basis. And we may note, in passing, that the point of origin cannot be located with precision either for the second dorsal, or for the pelvics because of the shapes of these fins.

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[1] The illustration of the only other member of the genus, *H. curtis-jamesi* Townsend and Nichols 1925, from off lower California (Townsend and Nichols, 1925, Fig. 2) suggests that the specimen was a female; and in any case it was too small (6 inches) to show this character, even if actually a male.

Species	Length, to rear base of 2nd dorsal mm.	Sex	Ratio, base 2nd dorsal to distance gill opening to pelvics
atlantica	727	♂	1.0 : 0.98
"	755	♂	1.0 : 1.09
"	770	♀	1.0 : 1.0
"	825	♀	1.0 : 1.08
"	856	♀	1.0 : 1.0
"	880	♀	1.0 : 1.0
pacifica	575	♂	1.0 : 1.0
"	590	♂	1.0 : 1.0

According to Holt and Byrne (1910, p. 19, Fig. 3, and Footnote) a second difference between *atlantica* and *pacifica* is that the "posterior limbs" of the forked canal that runs rearward along the lower surface of the snout, end blind in *atlantica*, but join the median anterior loop of the angular canal[1] in *pacifica*. Examination, however, of the two specimens of *pacifica* in the Museum of Comparative Zoology shows that they actually end blind in that form, as they do in *atlantica*, though the blind termination may lie very close to the median loop of the angular canal, on one side of the head or the other, on some specimens, both of *pacifica* and of *atlantica*, perhaps on both sides in some cases. Garman's (1904, Pl. 2, fig. 2) illustration of the lower

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[1] Nomenclature according to Garman (1888) and Bigelow and Schroeder (1953, p. 530, Fig. 119A).

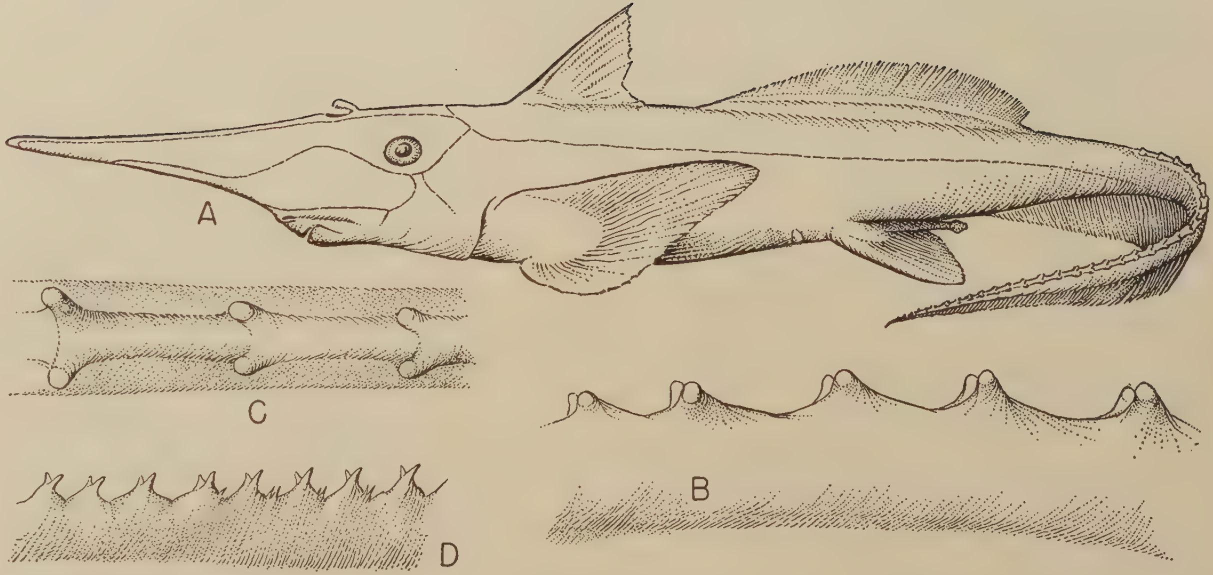

Fig. 5. *A, Rhinochimaera atlantica* Holt and Byrne, 1909, adult male, 1130 mm. long to upper termination of caudal fin. Nova Scotian slope. M.C.Z. No. 38244. *B* and *C,* Lateral and dorsal views of upper margin of anterior part of caudal fin of same, to show the tubercles, about 1.7 x. *D, Rhinochimaera pacifica,* adult male, 885 mm. long, Japan, M.C.Z. No. 1314, side view of upper margin of anterior part of caudal, about 1.7 x.

surface of the snout of *pacifica* is not clear in this respect.

Neither have we found anything to differentiate the Atlantic form (Fig. 5) from the Japanese, either in proportional dimensions, in the shapes, sizes or relative positions of the fins, in the nature of the dorsal spine (described for *atlantica* on p. 76), or in the shapes of the dental plates, which are as free from any trace of grinding prominences in the one as in the other. But our specimens do suggest that the caudal filament may average significantly longer on Japanese specimens than on Atlantic. Thus it is almost as long as the second dorsal fin in one of our *pacifica* and is pictured as about 70 per cent as long as that fin by Dean (1904, Pl. 1, fig. 4), whereas it is only about 10 per cent as long as the base of the second dorsal on one of our *atlantica* specimens on which it seems to be intact, while it is pictured as very short, indeed, by Holt and Byrne (1910, Pl. 3) for the type specimen. It seems, too, that the denticulations (single or paired) with which the upper margin of the caudal fin is armed, on large specimens, are not only more numerous on the Japanese form than on the Atlantic, but that they are regularly present on the females of the former, as well as on the males, but only on some of the females of the latter. Thus there are 47 and 52 series, respectively, on the two adult males of *pacifica* that we have examined, with "over fifty" reported for it by Dean (1904, p. 6), while his illustrations of an adult female (Dean, 1904, Pl. 1, figs. 1, 4) show them as rather prominent and as distributed continuously all along the caudal. But they number only 25 and 30, respectively, on our two adult Atlantic males; only one of our four large Atlantic females shows traces of them all along the caudal; the caudals of two of them are perfectly smooth; and they are much smaller on females where they are to be detected at all than they are on adult males. On the other hand, they are larger, relatively, on the large Atlantic males (Fig. 5) than on the Japanese.

In estimating the taxonomic significance of these differences, we face the puzzling fact that the caudal denticulations of one of the Japanese males resemble those of the Atlantic males in their low, rounded form, with the interspaces smooth edged between them. But they are sharp pointed (whether single or in pairs) on the other Japanese male of about the same size, with the intervening spaces interrupted, in most cases, by 1-3 much smaller, pointed denticles, as pictured by Garman (1904, Pl. 4, fig. 2) many years ago for this same specimen, and by us more recently (1953, Fig. 122).

It must remain an open question, until half-grown males can be examined, whether this difference between two specimens, both of which seem to be mature, represents two extremes of individual variation, or whether one of these conditions (and if so, which of them) precedes the other, as a given male becomes active, sexually.

To sum up, the North Atlantic population of *Rhinochimaera* seems to differ certainly from the Japanese only in a secondary sexual character that is subject to considerable variation from specimen to specimen, and perhaps in the proportional length of a structure (caudal filament) so susceptible to damage that estimates of its length are largely a matter of guesswork for a large proportion of the specimens that have come to hand. Were we facing the question *de novo* we would hesitate to separate the Atlantic form from the Pacific, specifically, on such slender bases. However, since the name *atlantica* is in use already, we are content to let it stand for the time being. Reduction to the rank of subspecies may be its ultimate fate.

The general morphology of *Rhinochimaera pacifica,* internal as well as external, was made well known by Garman's (1904) and Dean's (1904) studies, accompanied by beautiful illustrations. The following details for *atlantica,* additional to Holt and Byrne's (1910) account, are based on the "Cap'n Bill II" specimens.

The rear edges of the dorsal fin-spine are perfectly smooth on all the large specimens, as noted by Holt and Byrne (1910, p. 18). But they are rough with minute serrations along the outer third of their length on a female 457 mm. long; evidently they are lost during later growth. Holt and Byrne's illustration (1910, Pl. 3) suggests, further, that the spine is attached to the fin right out to its tip (they do not comment on this), not free toward the tip as it is in *Harriotta* (p. 83). And this seems to be the normal state, being true of one of our large females, and of the largest male as well. But the union must be a feeble one, for the membrane is free from the fin along its outer ⅓-⅔ on all our

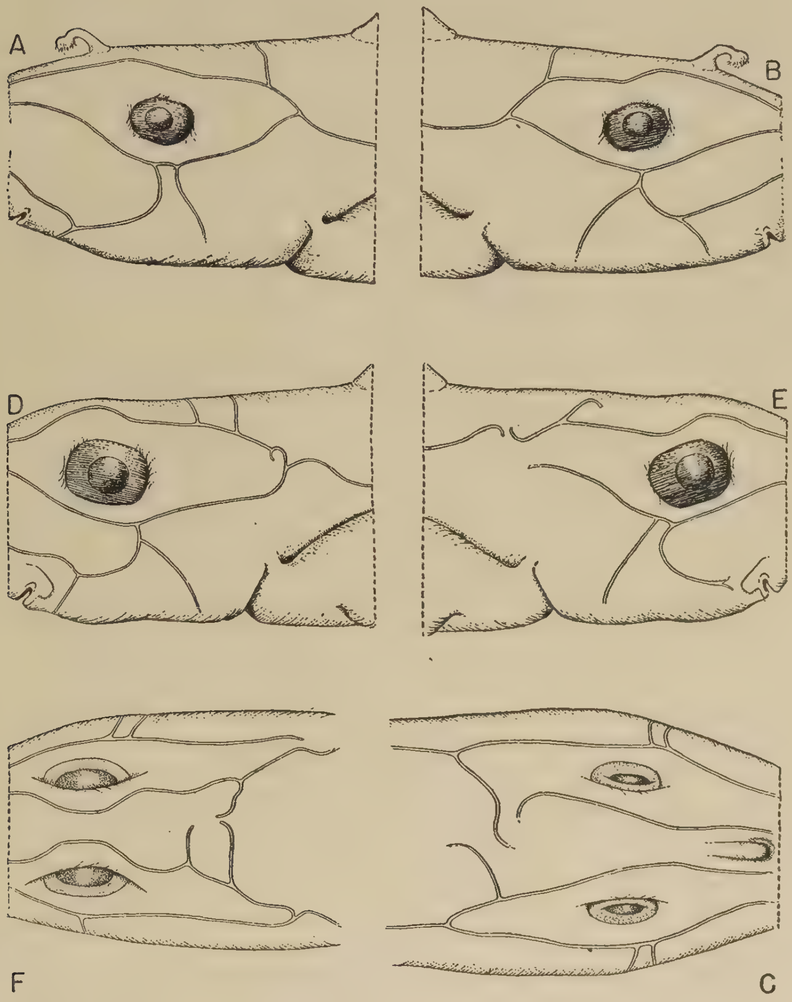

Fig. 6. Diagrams showing pattern of mucous canals on head. *A, Rhinochimaera atlantica,* same specimen as in Figure 5, left side. *B,* Same specimen, right side. *C,* Dorsal view of male, 1034, mm. long to upper termination of caudal fin, M.C.Z. No. 38243. *D, Harriotta raleighana,* female, 840 mm. long to upper termination of caudal fin, M.C.Z. No. 38247, left side. *E,* Same specimen, right side. *F,* Same specimen, dorsal view.

other specimens, including a female only 450 mm. long, without any clear sign that the separation had been a forcible one.

Our specimens corroborate Holt and Byrne's (1910, p. 21) suggestion that the pattern of mucous canals on the sides of the head is a variable character, as it is in *Harriotta* (p. 83). It seems usual for the jugular canal and the oral canal to branch off separately from the orbital canal below the eye, with the two separated by a longer or shorter interspace. But it is only on one side of the head that this is the case on one of the large females, and on one of the large males; on the other side of the head of each of these individuals the jugular canal and the oral canal branch from the orbital as a single trunk which bifurcates some little distance outward from its point of departure from the orbital (Fig. 6*A*, *B*). It proves, too, that the canal pattern on the crown is variable, also. Normally, the cranial canals of the two sides are connected across the back of the head by a cross-canal known as the aural.[1] But the aural is interrupted, midway, both on one of our specimens of *pacifica* (see Garman, 1904, Pl. 2, fig. 1) and on our 457 mm. female of *atlantica*, with its two parts overlapping. And one of the large males of *atlantica* shows a still more aberrant state, with the left-hand cranial canal recurving forward toward the mid line of the head to end blind, with the aural canal interrupted (Fig. 6*C*). The large pores, also, on the sides of the head, vary in number, not only from specimen to specimen, but between the two sides of the head on some specimens. A count of 13 below the cranial canal on the left-hand side of the head of our largest male *atlantica*, in the region between eye and frontal tenaculum, but of 10 on the right-hand side, may serve as an illustration. The presence of a few sharp denticles on the mid line of the back between second dorsal fin and caudal, also on the nape, on an *atlantica* so small (151 mm. long) as evidently to have been hatched recently, deserves mention, also.

Rhinochimaera atlantica resembles its relative *Harriotta raleighana* so closely in general appearance that the one might be mistaken for the other on cursory examination, especially since the two are likely to be taken together in trawl hauls at appropriate depths on the slope, as happened on "Cap'n Bill II" on four occasions off southwestern Nova Scotia. But it is easy to tell partly grown specimens apart, on closer inspection. Thus the glossy smoothness of the dental plates of *Rhinochimaera* contrasts strongly with the grinding ridges and knobs that develop on the dental plates of *Harriotta,* soon after hatching; also, the eyes of *Rhinochimaera* are noticeably smaller than those of *Harriotta* at all stages in growth as appears from the following comparative table:

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[1] Nomenclature according to Garman (1888, Pls. 1, 2, 4) and Bigelow and Schroeder (1953, p. 530, Fig. 119).

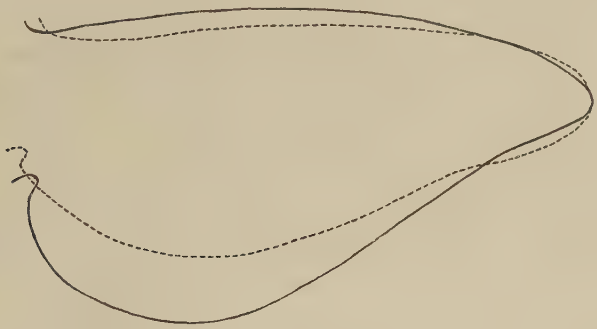

Fig. 7. Tracings of pectoral fins, adjusted to equal lengths along outer margin, to show difference in shape; solid line, *Harriotta raleighana,* female about 908 mm. long to upper termination of caudal fin, M.C.Z. No. 37726; broken line, *Rhinochimaera atlantica,* female about 1282 mm. to upper termination of caudal fin, M.C.Z. No. 37735.

Species	Length, to termination of upper caudal[1] mm.	Sex	Ratio, horizontal diameter of eye to distance eye to base of dorsal spine
Rhinochimaera atlantica	1034	♂	1.0 : 2.80
	1130	♂	1.0 : 2.66
	1184	♀	1.0 : 3.17
	1282	♀	1.0 : 2.43
	1290	♀	1.0 : 3.03
	1295	♀	1.0 : 3.07
Harriotta raleighana	283	♀	1.0 : 1.78
	447	♂	1.0 : 1.65
	758	♂	1.0 : 1.63
	840	♀	1.0 : 2.00
	885	♀	1.0 : 1.85
	908	♀	1.0 : 2.13

[1] Approximate measurement

The pectoral fins are noticeably narrower toward the base in *Rhinochimaera* than in *Harriotta* but with more broadly rounded tip (Fig. 7). The rear edges of the dorsal fin-spine, which are serrate in small specimens of both fish, and are serrate to maturity in *Harriotta,* are perfectly smooth on large examples of *Rhinochimaera,* male as well as female. And the lateral mucous canal, which runs nearly straight rearward from its point of departure from the occipital canal in *Rhinochimaera,* or slopes slightly downward (Fig. 5*A*), bows upward at first, then turns downward — rearward in *Harriotta.*

More conspicuous differences between specimens of the two fish that are nearing sexual maturity are that the upper margin of the caudal fin thickens in *Rhinochimaera*, while developing a row of prominent denticulate structures in the males (also in some females), but with the tip of the snout continuing smooth and soft, whereas in *Harriotta* the upper caudal continues thin and smooth-edged in both sexes, but the tip of the snout stiffens in the males (not in females), bends upward, and develops a double series of rounded knobs.

It is probable that *R. atlantica* is more widespread and more plentiful in the eastern side of the Atlantic than the paucity of the previous records (one adult specimen and a few egg cases from the Irish Atlantic slope) might suggest, for this is certainly the case in the west, where "Cap'n Bill II" took it at 6 stations off southwestern Nova Scotia, at 1 station on the slope of Georges Bank, and at 1 station in the offing of New York. A table follows of localities, depths, and number, size and sex of the specimens:

Length to termination of upper caudal[1]	Total length	Sex	Lat. N.	Long. W.	Depth in fathoms	Date
151[2]	151	♂	42°22′	64°55′	290-340	7/15/53
436	457	♀	42°40′	63°51′	465-480	7/26/52
1034	1060	♂	38°52′	72°51′	415-440	6/27/53
1130[2]	1130	♂	42°40′	63°54′	520-545	7/12/53
1184	1202	♀	40°07′	68°30′	420-480	7/13/52
1282	1315	♀	42°14′	65°10′	490-530	7/28/52
1290	1315	♀	40°11′	68°16′	480-490	7/14/52
1295	1315	♀	42°38′	64°10′	460-475	7/13/53

[1] Approximate measurement
[2] Filament lost

It seems that *Rhinochimaera* is considerably less plentiful than *Harriotta* off Nova Scotia and off New England judging from the fact that four times as many specimens of *Harriotta* (32) as of *Rhinochimaera* (8) were taken by "Cap'n Bill II."

HARRIOTTA RALEIGHANA Goode and Bean 1895

Nine specimens of this long-nosed chimaeroid had been reported previously from the western side of the Atlantic, from the trawlings made by the "Albatross" in the 1880's (Goode and Bean, 1895, p. 33), by the Prince of Monaco in 1913 (Roule and Angel, 1933, p. 75) and by "Caryn" of the Woods Hole Oceanographic Institution in 1949 (Bigelow and Schroeder, 1953, pp. 551, 552) at localities scattered along the continental slope from the offing of Chesapeake Bay to the offing of Halifax, Nova Scotia. Three specimens, also, were taken in the eastern side of the Atlantic by the "Michael Sars" in 1910 (Koefoed, 1927, p. 29), one of them near the Canaries, the other two west of Scotland. We can now report the capture, by "Cap'n Bill II," of 26 specimens of both sexes in 1952, and of 6 more in 1953, ranging from partly grown to adults.

Specimens of *Harriotta* taken by "Caryn" in 1949,
and by "Cap'n Bill II" in 1952 and 1953,
arranged in latitudinal sequence, south to north

Lat. N.	Long. W.	Depth fath.	Date	No.	Sex	Length in mm. to termination of upper caudal[1]	to tip of filament
38°43′	72°56′	630-675	June 30, 1953	1	♀	256	329
39°49′	70°05′	710-730	July 28, 1953	1	♂	375	456
40°07′	68°30′	420-480	July 13, 1952	1	♀	850	900
40°10′	68°16′	490	July 14, 1952	3	♂	702-748	742-837
41°25′	65°54′	415-490	June 19, 1949	2	♂ ♀	126-730	155-770
42°14′	65°10′	490-530	July 28, 1952	5	♂ ♀	157-447	283-550
42°16′	65°08′	370-420	July 28, 1952	2	♀	885-925	946[2]
42°22′	64°55′	290-340	July 15, 1953	1	♀	840	948
42°38′	64°04′	440-460	June 17, 1949	1	♂	735	773
42°38′	64°10′	460-475	July 13, 1953	1	♂	758	836
42°39′	63°58′	520	July 26, 1952	5	♂ ♀	283-756	373-870
42°39′	64°00′	610-625	July 12, 1953	1	♀	865	1025
42°40′	63°51′	465-480	July 26, 1952	3	♂ ♀	188-716	249-792
42°40′	63°54′	520-545	July 12, 1953	1	♂	?	775
42°40′	64°00′	440-450	June 17, 1949	1	♂	705	818
42°41′	63°49′	465-480	July 26, 1952	4	♂	250-721	295-815
42°41′	64°02′	385-400	July 27, 1952	3	♂ ♀	741-908	832-935

[1] Approximate measurement
[2] Tail lost on 925 mm. specimen

The fact that 30 of the total of 36 specimens were taken in the offing of southwestern Nova Scotia, and that 6 of the 12 successful hauls that were made there in 1952, at the appropriate depths, yielded *Harriotta,* shows that this chimaeroid is more plentiful along this part of the slope than earlier records for it might have suggested. The proportion of hauls yielding it in this region was somewhat lower in 1953 (4 out of a total of 10), though the trawlings of that summer seem to have been equally successful in general, to judge from the catches of fishes of other kinds. It appears to be less plentiful to the westward of longitude about 66°W than to the eastward, for ''Cap'n Bill II'' took it in only 4 hauls (6 specimens) along the slope of Georges Bank, and to the westward, out of a total of 41 hauls that she made there at 400 to 730 fathoms, in the summers of 1952 and 1953 combined.

On the Nova Scotian slope the upper limit to the regular occurrence of *Harriotta* appears to lie at about 400 fathoms although a few specimens were taken as shoal at about 340 fathoms. ''Cap'n Bill II'' took *raleighana* down to 710-730 fathoms, the Prince of Monaco at 728 fathoms (1332 meters, Roule and Angel, 1933, p. 75), the ''Albatross'' trawled it at 1081 fathoms off Marthas Vineyard, at 991 fathoms off New York, at 707 fathoms off New Jersey and at 781 fathoms off Chesapeake Bay. Depth records for it in the eastern Atlantic are 1014 fathoms (1853 meters) west of Scotland, and 1423 fathoms (2603 meters) near the Canaries (Koefoed, 1927, p. 29).

The external aspect of *H. raleighana* has been made well known by the successive studies of Goode and Bean (1895, p. 32), Koefoed (1927, p. 29), Roule and Angel (1933, p. 75), and Bigelow and Schroeder (1953, p. 551). Examination of the ''Cap'n Bill II'' series adds the following details.

A — Dermal denticles and dorsal fin-spine. No trace of the juvenile dermal denticles is to be seen (or felt) on specimens more than about 485 mm. long to the rearmost visible rays of the upper side of the caudal fin. A female of 300 mm. (measured similarly) still has one pair of supra-oculars, one pair on the midline of the back in the space between the first and second dorsal fins, and 4 pairs between the second dorsal and the caudal.

The increase in the size of the dorsal fin-spine with growth is not accompanied by a corresponding increase in the size of the serrations along the rear margin of the spine, hence the latter does not feel any rougher, to the touch, on large specimens than on those of medium size. And the serrations may be partly obliterated by maturity, on some individuals, perhaps wholly so. The "Cap'n Bill II" series also verify earlier accounts of the spine as free from the margin of the fin along at least its outer half. This contrasts with the condition in *Rhinochimaera atlantica,* where the spine is smooth edged from a very early stage in growth, and where it is attached to the fin-margin, right out to its tip, or nearly so (p. 76).

B — Caudal filament. When intact, the caudal filament may be as much as 33-44 per cent as long as from snout to last visible caudal fin-ray among the smaller specimens (191-263 mm., total length). On three of our larger males (680-750 mm., total length) the filament is 111-116 mm. long, and 160 mm. on our largest female (1025 mm., total length). But it is so thread-like toward its tip that there is always a possibility that part of it may have been lost, even on specimens on which it seems to be intact.

C — Pattern of mucous canals on head. Cumulative evidence is conclusive, that the pattern of mucous canals on the head varies too widely to have much significance in taxonomy, not only between different individuals, but even between the two sides of the head of a single individual in many cases. On three of the larger males, for example, the jugular canal and the oral diverge jointly from the orbital canal on one side of the head, but separately on the other side with an interspace between them (Fig. 6*D, E*). When they arise jointly they may separate at once or they may run for a longer distance or a shorter as a joint trunk before they diverge, one from the other. On one specimen of each sex the jugular canal fails to connect with the orbital on either side of the head, while on one male it ends blind on the right-hand side but connects with the orbital on the left-hand side.

D — Snout, and sexual tenacula. In *H. raleighana* the snouts of the males are similar to those of the females, up to a length of 450 mm. or so (to last visible caudal rays); and no trace is to be seen of the frontal tenaculum, or of the prepelvic tenacula, although the prepelvic pockets are already formed on newly hatched specimens. But the tip of the snout has begun to curve upward, its terminal knobs have formed, the sexual tenacula have developed in the males, and the claspers seem to be ready to function by the time a length of about 650 mm. (to last caudal rays) has been reached.

The largest male yet recorded is about 836 mm. in total length (758 mm. to last visible caudal ray). A female 990 mm. in total length including a caudal filament of about 125 mm. as scaled from Roule and Angel's (1933, Pl. 4, figs. 34-34a) illustration, and another 1025 mm. in total length, including caudal filament of 160 mm. (Cap'n Bill II'' specimen) are the largest yet seen of that sex.

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H. Stommel:

Exploratory Measurements of Electrical Potential Differences between Widely Spaced Points in the North Atlantic Ocean.

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(Woods Hole Oceanographic Institution, Woods Hole, Mass.)

Exploratory Measurements of Electrical Potential Differences between Widely Spaced Points in the North Atlantic Ocean[1].

By

H. Stommel.

With 2 Figures.

Abstract. Electrical potential measurements between various points in the North Atlantic Ocean are discussed, and possible implications concerning the semidiurnal tide and resistivity of the ocean bottom are described. Points of measurement include Halifax, New York, Bermuda, Turks Island, England, Azores, Cape Verde Islands.

Zusammenfassung. Es werden Messungen des elektrischen Potentials zwischen verschiedenen Punkten des Nordatlantischen Ozeans diskutiert und mögliche Folgerungen hinsichtlich der halbtägigen Gezeiten und des Widerstands des Meeresbodens erörtert; die benützten Messungen umfassen Halifax, New York, Bermuda, Turks-Insel, England, Azoren, Kap-Verde-Inseln.

Résumé. L'auteur discute des mesures du potentiel électrique effectuées entre différents points de l'océan Atlantique septentrional et décrit les conséquences possibles quant aux marées semi-diurnes et à la résistance du fond de l'océan. Les mesures utilisées englobent Halifax, New York, les Bermudes, Turks Island, l'Angleterre, les Açores et les îles du Cap Vert.

I. Introduction.

Longuet-Higgins (1949) showed that the part of the potential gradient across the English Channel which varies with a semidiurnal lunar period is caused by the e. m. f. induced by tidal currents moving through the Earth's magnetic field. He developed a theory for the potential field produced by water moving in an infinite channel of semielliptical cross section. The bed of the channel was taken with uniform conductivity. Consideration of the various parameters entering into the problem showed that the English Channel was a fairly critical case in the following sense: if the bottom conductivity had been greater, or the ratio of width to depth greater, then the potential gradient across the channel would have been reduced to a small fraction of the induced e. m. f. In fact, however, the bottom of the English Channel does not short-circuit the e. m. f. induced in the water so that the potential gradient actually observed is an appreciable fraction of the induced e. m. f. A qualitative consideration of the geometry of the North Atlantic Ocean basin indicates that the ratio of width to depth is not unlike the English Channel. The conductivity of bottom rocks, if different, may be supposed to be smaller than those beneath the English Channel. On the whole, therefore, one anticipates that potential differences of the order of one volt or so will be produced across the ocean by deep sea tidal currents. The purpose of this paper is to report the results of some short series of exploratory measurements made between various points in the North Atlantic Ocean. The measurements were made using existing submarine telegraph cables.

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II. Methods of measurement.

With the exception of three nights on the Halifax-Bermuda-Turks Island cable all measurements were made on cables carrying traffic. On this account no special provisions for elimination of electrochemical potentials at the earth connections were possible. Therefore no geophysical significance ought to be attached to the mean value of each set of measurements because in each case it probably represents the degree of polarization of the earth connection as much as anything else. On three nights in February it was possible to make measurements on the Halifax-Bermuda-Turks Island cables with all telegraphic connections removed. Measurements were made potentiometrically at Bermuda. At Halifax and Turks Island the cable ends were directly connected to the long sea-earths. In addition a series of hourly readings of the fork relays at Bermuda was also made for almost the whole month, and it was quite obvious from comparison of the two types of reading that the fork relay light scale gives a fairly good indication of the difference of potential existing between the ground connections at the two ends of the cable. Further measurements at Horta on the cables to Halifax (Nova Scotia), Porthcurno (England) and St. Vincent (Cape Verde Islands) were made by reading the fork relay light scales directly. A longer series of measurements on the New York to Horta cable was made by directly connecting a Speedomax recorder to the input at New York. This latter cable is operated Simplex, and the input is transformer coupled to the receiving apparatus. Thus a Speedomax can be used to read the low frequency earth potentials at the cable end. All the other cables are operated Duplex, and it would be difficult to connect recording apparatus into the delicately balanced bridge without upsetting communications. No alterations to the Duplex networks were made except for calibration and determination of the corrections for zero-drift of the amplifiers.

The points between which measurements were made, and the schematic routes of the cables used in the measurements are shown in Figure 1.

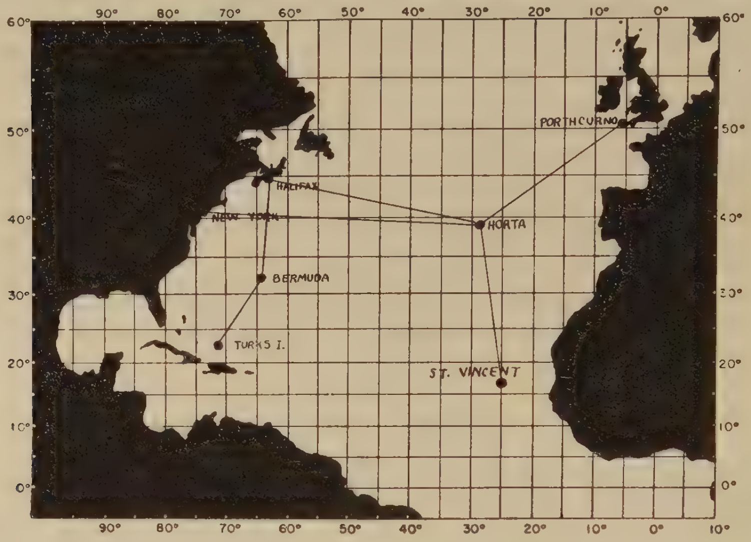
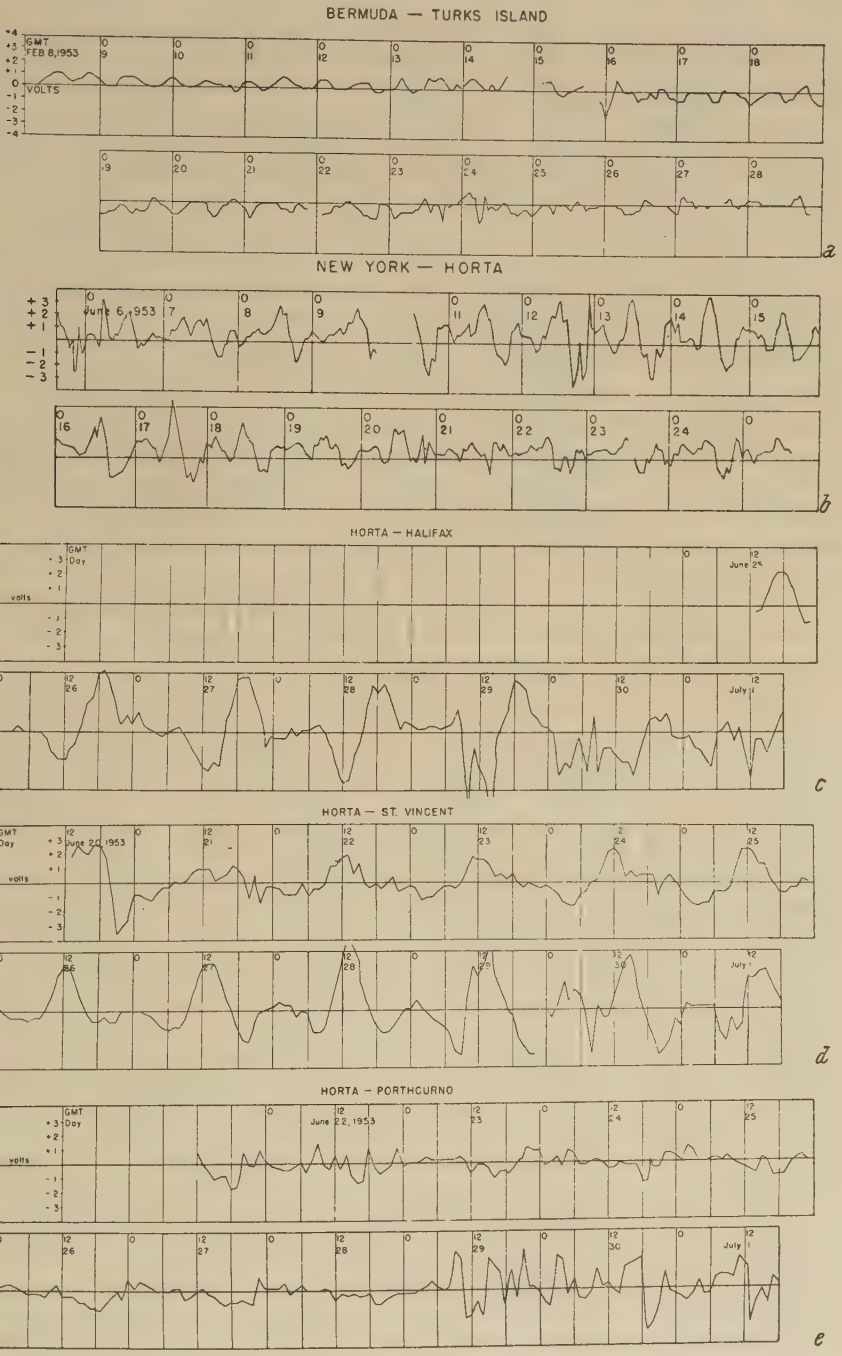


Fig. 1.

III. The Halifax-Bermuda-Turks Island measurements and their interpretation.

The existence of a lunar semidiurnal period is very obvious to the eye in the Halifax-Bermuda and Bermuda-Turks Island measurements. Figure 2 shows fork relay readings made from Bermuda to Turks Island. A harmonic analysis of the graph for this cable and for the one from Halifax to Bermuda indicates a total Halifax to Turks Island amplitude of 1.2 volts in the semidiurnal lunar component, Halifax being most positive with respect to Turks Island at three hours after Greenwich Transit of the Moon.

If we now attempt to identify this observed semidiurnal lunar component of potential difference with the induced potentials associated with tidal currents, we are confronted with two very serious types of difficulty: first, that ocean basins are of such complex shape that precise transformation from velocity field to potential field is a problem which would require a very large amount of numerical computation; and secondly, very little is known about the distribution of tidal currents in the deep ocean areas of the North Atlantic Ocean. To meet the first of these difficulties we note that an order of magnitude idea of the tidal velocity



BERMUDA — TURKS ISLAND

NEW YORK — HORTA

HORTA — HALIFAX

HORTA — ST. VINCENT

HORTA — PORTHCURNO

Fig. 2.

Table I. *Halifax-Bermuda and Bermuda-Turks Island Potential Differences (volts).*

Feb. 15			Feb. 22			Mar. 1		
GMT	Halifax-Bermuda	Bermuda-Turks Is.	GMT	Halifax-Bermuda	Bermuda-Turks Is.	GMT	Halifax-Bermuda	Bermuda-Turks Is.
	volts			volts			volts	
0230	— 0.14	+ 0.61	0200	+ 0.20	— 0.93	0200	+ 0.40	+ 0.0
0330	— 0.08	+ 0.86	0300	+ 0.15	— 0.84	0300	+ 0.55	+ 0.15
0430	— 0.01	+ 0.77	0400	+ 0.00	— 0.84	0400	+ 0.55	+ 0.15
0530	+ 0.14	+ 0.84	0500	+ 0.20	— 0.74	0500	+ 0.25	+ 0.15
0630	— 0.12	+ 0.50	0600	+ 0.45	— 0.24	0600	— 0.15	— 0.5
0730	— 0.99	+ 0.08	0700	+ 0.55	— 0.24	0700	+ 0.10	— 0.6
0830	— 1.36	— 0.36	0800	+ 0.60	— 0.29	0800	— 0.35	— 0.6
0930	— 1.54	— 0.44	0900	+ 1.00	— 0.15	0900	— 0.55	— 0.95
1030	— 1.88	— 0.40	1000	+ 1.40	+ 0.10	1000	— 1.0	— 0.9
1115	— 1.86	— 0.27	1100	+ 1.21	+ 0.10	1100	— 0.9	— 0.9

Table I *(Continued). (Fork Relay)*

GMT	Feb. 8	9	10	11	12	13	14	15	16	17
0000	—	+ 0.5	+ 0.8	+ 0.5	+ 0.5	0.0	+ 0.3	—	— 2.0	—0.8
0100	—	0.0	+ 0.5	+ 0.5	+ 0.8	0.0	+ 0.5	—	— 1.5	—0.8
0200	—	0.0	+ 0.3	+ 0.5	+ 0.8	0.0	+ 0.8	—	0.0	—0.8
0300	—	0.0	+ 0.3	+ 0.3	+ 0.8	+ 0.5	+ 1.0	—	0.0	—0.3
0400	0.0	0.0	0.0	+ 0.3	+ 0.5	+ 1.0	+ 1.0	—	+ 1.0	0.0
0500	+ 0.3	0.0	0.0	0.0	0.0	+ 0.5	+ 0.5	—	+ 0.5	0.0
0600	+ 0.4	+ 0.5	— 0.3	— 0.3	0.0	+ 0.3	+ 0.5	—	0.0	+ 0.3
0700	+ 0.6	+ 0.8	0.0	0.0	0.0	0.0	+ 0.3	—	0.0	+ 0.5
0800	+ 0.8	+ 0.8	0.0	0.0	0.0	— 0.3	0.0	—	0.0	+ 0.3
0900	+ 1.0	+ 0.8	+ 0.3	+ 0.3	0.0	0.0	0.0	—	0.0	0.0
1000	+ 1.0	+ 0.8	+ 0.5	+ 0.5	0.0	0.0	+ 0.5	—	— 0.3	0.0
1100	+ 1.0	+ 0.8	+ 0.5	+ 0.5	+ 0.3	0.0	0.0	—	— 0.8	—0.3
1200	+ 0.8	+ 0.5	+ 0.5	+ 0.8	+ 0.3	+ 0.5	0.0	0.0	— 0.5	—0.8
1300	+ 0.5	+ 0.5	+ 0.3	+ 1.0	+ 0.5	+ 1.0	+ 0.5	+ 0.3	— 0.5	—0.8
1400	+ 0.3	+ 0.5	+ 0.3	+ 0.8	+ 0.5	+ 0.8	+ 0.8	+ 0.3	— 0.5	—0.8
1500	+ 0.3	0.0	+ 0.3	+ 0.8	+ 0.5	+ 0.8	+ 1.3	+ 0.3	0.0	0.0
1600	+ 0.5	0.0	+ 0.3	+ 0.3	+ 0.5	+ 1.0	+ 1.0	+ 0.5	— 0.3	+ 0.3
1700	+ 1.3	0.0	0.0	+ 0.3	+ 0.3	+ 1.0	—	—	— 0.5	0.0
1800	+ 0.5	0.0	0.0	+ 0.3	0.0	+ 0.8	—	—	+ 0.3	0.0
1900	+ 0.8	0.0	+ 0.3	0.0	— 0.3	+ 0.3	—	—	+ 0.3	0.0
2000	+ 1.0	+ 0.3	— 0.3	0.0	— 0.3	0.0	—	—	+ 0.3	0.0
2100	+ 0.8	0.0	— 0.5	+ 0.3	— 0.3	0.0	—	— 0.8	— 0.3	—0.3
2200	+ 0.5	+ 0.3	— 0.3	0.0	0.0	+ 0.5	—	— 1.0	— 0.5	—0.4
2300	+ 0.8	+ 0.8	+ 0.3	+ 0.3	0.0	+ 0.3	—	— 2.0	— 0.5	—0.5

which would be required to produce the observed component of potential difference can be obtained by computing the mean velocity of tidal current required in a channel of infinite length, but with a width and depth equal to that actually existing between the two points of measurement. The chief excuse for this rather lame artifice is its simplicity; moreover it sets a lower limit on the possible tidal velocity the actual mean velocity is not likely to be less, although it may be more, than the equivalent infinite channel velocity.

The second difficulty, our virtual ignorance of the actual deep sea tidal currents, may be met in two ways: there are a few series of current measurements made at anchor stations, and there are also various tidal theories and cotidal charts from which we can compute tidal currents for comparison with the electrical measurements.

There are no satisfactory deep sea tidal current measurements along the eastern coast of North America to compare with the Halifax-Turks Island electrical measurements. By a happy chance, however, it so happens that the time of high water of the semidiurnal lunar component at Bermuda, and all open coastal stations along the North American mainland from Halifax to Turks Island is practically the same, so that

Bermuda–Turks Island.

18	19	20	21	22	23	24	25	26	27
—1.0	—1.0	—1.0	—0.5	—	—0.3	+0.3	—1.0	0.0	—0.8
—1.0	—1.0	—1.0	—0.8	—	—0.5	+0.5	—0.8	0.0	—0.8
—0.8	—1.0	—1.0	—1.3	—	—1.3	+0.8	—0.5	0.0	+0.5
—0.5	—0.8	—0.8	—0.8	—	—1.0	+1.0	0.0	0.0	+0.8
—	—0.8	—0.5	—0.3	—	—0.8	+0.5	0.0	0.0	+0.3
—0.3	—0.8	—0.3	0.0	—	—0.8	+0.3	0.0	—0.3	+0.3
0.0	—0.5	0.0	0.0	—	—0.8	—1.5	—0.3	—0.3	+0.3
0.0	—0.3	0.0	0.0	—	—0.8	—1.3	—0.8	—0.8	—0.3
0.0	—0.3	0.0	0.0	—	—0.8	+0.8	0.0	—0.8	0.0
0.0	—0.5	0.0	0.0	—	—0.5	—0.5	0.0	—0.8	0.0
0.0	—0.8	0.0	0.0	—	—0.5	—0.3	0.0	—0.8	0.0
—0.3	—1.0	0.0	0.0	—	0.0	—0.5	0.0	—0.5	—0.3
—0.8	—0.5	—0.8	—0.5	—	+0.5	—0.5	—0.3	—0.5	0.0
—0.8	—0.8	—1.0	—0.5	—0.3	0.0	—0.3	—0.5	0.0	—
—0.5	—0.8	—1.3	—0.5	—0.5	—0.8	0.0	0.0	+0.5	—
—0.5	—0.8	—1.0	—0.8	—0.8	0.0	0.0	+0.3	+0.3	—
0.0	—0.5	—0.5	—0.8	—1.0	0.0	—0.3	0.0	0.0	—
+0.3	+0.3	—0.3	—0.3	—1.0	—0.3	—0.8	0.0	0.0	—
+0.5	+0.5	—0.3	0.0	—1.3	—1.5	—0.8	—0.5	0.0	—
+0.8	+0.3	0.0	—0.3	—1.3	0.0	—1.0	—0.3	0.0	—
0.0	0.0	+0.3	—0.5	—1.3	—0.3	—0.8	—0.3	0.0	—
—0.5	—0.3	+0.3	—0.5	0.0	0.0	—0.5	—0.3	0.0	—
—0.8	—0.3	0.0	—	0.0	0.0	—0.5	—0.3	—0.3	—
—1.0	—0.5	—0.3	—	0.0	0.0	—0.8	0.0	—0.5	—

Table II *New York-Horta*

GMT	June 5	6	7	8	9	10	11	12	13	14
0000	—	+0.5	+0.2	+0.3	+0.9	—	+1.5	+0.7	+1.3	+1.9
0100	—	+0.7	+0.2	—0.5	+0.6	—	+0.9	+0.7	+0.9	+2.1
0200	—	+0.7	0.0	—0.3	+0.4	—	+0.1	+0.5	+1.2	+1.0
0300	—	0.0	+0.9	+0.5	+0.2	—	+0.7	+0.5	+1.9	+1.8
0400	—	—0.5	+0.8	+0.4	0.0	—	+0.6	—0.1	+1.6	+0.2
0500	—	+3.5	+1.1	+0.7	+0.4	—	+0.9	—0.7	+0.4	+0.3
0600	—	+2.6	+1.7	+0.8	+0.6	—	+1.1	—0.3	—0.3	+0.5
0700	—	+0.1	+1.9	+1.0	+0.6	—	+1.7	+0.7	—0.7	+0.3
0800	—	0.0	+1.1	+0.7	+0.7	—	+0.5	+0.4	—0.6	—0.4
0900	—	+0.5	+0.5	+0.5	—1.2	—	+0.9	+1.4	+0.3	—0.4
1000	—	+0.4	+1.1	+0.8	—0.6	—	+2.2	+2.2	+0.5	+1.8
1100	—	+1.4	+1.5	+1.0	+0.8	—	+2.9	+2.0	+1.2	+2.5
1200	—	+1.8	+1.7	—1.4	+1.5	—	+3.2	+3.3	+3.2	+3.8
1300	—	+2.3	+1.2	—2.0	—	+2.4	+2.4	+3.3	+3.6	+3.5
1400	—	+1.7	+1.8	+2.9	—	+1.5	+1.9	—	+2.8	+2.4
1500	+1.2	+0.5	+1.0	+2.2	—	+0.6	0.0	+2.0	+1.9	+0.9
1600	+1.1	—0.7	—0.2	+2.4	—	—1.1	—0.8	—0.6	—0.5	—1.0
1700	+0.3	0.0	—1.0	+0.5	—	—1.8	—1.1	—3.5	—0.9	—1.4
1800	—0.7	—0.4	—1.2	—0.2	—	—2.5	—1.2	—2.3	—0.7	—2.0
1900	0.0	0.0	—1.1	—1.6	—	—1.2	—1.7	+0.3	—2.5	—1.7
2000	—4.0	+0.2	—0.2	—1.2	—	—1.5	—0.9	—2.8	—2.7	—1.5
2100	+1.0	+0.6	—0.1	—0.4	—	+1.2	+0.9	—2.0	—0.3	+0.7
2200	—1.1	+0.3	+0.9	+0.3	—	+1.2	+1.1	+4.0	—1.0	+0.5
2300	—0.5	+0.3	+0.9	+0.3	—	+1.5	+1.5	+2.5	—0.3	+1.5

we may regard the tidal system in this entire area as part of one loop of a standing wave. From the principle of conservation of mass, a knowledge of the mean amplitude of the tidal elevation over the area, and the geometry of the basin, the amplitude of the average (over the section) tidal current, and the time of maximum eastward flow may be obtained. The fact that the amplitude (1.2 cm/sec) and phase (3 hrs. Greenwich lunar time) of the tidal current as computed from the tidal elevation agree quite closely with the equivalent infinite channel velocity computed from the electrical measurements (0.9 cm/sec, 3 hrs. Greenwich lunar time) suggests that there is almost no shorting out due to the conduction of the bottom. In terms of order of magnitude one can say (using LONGUET-HIGGIN's formula) that the conductivity of the bottom between Halifax and Turks Island is not likely to be more than 2×10^{-5} (ohms-cm)$^{-1}$.

IV. Measurements on cables terminating at Horta and difficulties of interpretation.

Up to this point the story unfolds in comparatively simple, straightforward form, and then four months later when I made similar measure-

Potential Difference (volts).

15	16	17	18	19	20	21	22	23	24	25
+ 1.2	+ 1.1	+ 1.2	+ 0.7	+ 0.7	+ 0.7	+ 0.4	+ 0.5	+ 0.2	+ 0.9	+ 0.5
+ 1.2	+ 1.4	+ 1.2	+ 1.7	+ 0.8	+ 0.6	+ 0.4	+ 0.6	+ 0.5	—0.2	+ 0.8
+ 1.2	+ 1.2	+ 1.5	+ 1.2	+ 0.8	+ 0.6	+ 0.4	+ 0.5	+ 0.6	+ 0.2	+ 1.0
+ 1.0	+ 1.0	+ 1.5	+ 1.0	+ 0.9	+ 0.7	+ 0.5	+ 0.5	+ 0.7	—0.4	+ 0.2
+ 0.3	+ 1.0	+ 1.0	+ 0.5	+ 1.1	+ 1.0	+ 0.8	+ 0.8	+ 0.7	+ 0.7	0.0
+ 0.7	+ 0.8	+ 0.7	+ 0.7	+ 1.2	+ 1.0	+ 0.8	+ 0.7	+ 0.9	+ 1.5	+ 0.5
+ 0.4	+ 0.5	+ 0.7	+ 0.1	+ 1.0	+ 0.7	+ 2.8	+ 1.2	+ 0.8	+ 1.1	+ 0.7
—0.4	+ 0.2	—0.4	—0.2	+ 0.5	—0.1	+ 0.5	+ 1.0	+ 0.7	+ 0.8	+ 0.8
—0.4	+ 0.2	—0.4	+ 0.5	+ 0.3	—0.2	—0.1	+ 0.8	+ 0.5	+ 0.6	+ 0.8
—0.5	+ 0.4	+ 0.3	+ 0.8	0.0	—0.2	+ 0.9	+ 1.0	+ 0.6	+ 0.7	+ 1.0
+ 1.1	+ 1.0	+ 1.0	+ 2.1	+ 1.1	+ 0.7	+ 0.7	+ 1.0	+ 1.0	+ 1.0	+ 1.7
+ 1.7	+ 1.3	+ 2.0	+ 2.8	+ 1.0	+ 2.5	+ 1.0	+ 1.8	+ 1.2	+ 0.9	+ 1.8
+ 2.5	+ 2.5	+ 4.5	+ 2.0	+ 1.7	+ 1.8	+ 1.4	+ 1.8	+ 2.0	+ 1.7	+ 1.5
+ 2.5	+ 1.5	+ 3.5	+ 1.5	+ 1.4	+ 2.2	+ 0.8	+ 1.2	+ 1.5	+ 1.6	+ 1.1
+ 1.2	+ 3.2	+ 2.0	+ 1.1	+ 1.8	+ 2.2	+ 0.6	—0.5	—	+ 1.5	+ 1.0
+ 0.3	+ 2.2	+ 1.1	+ 0.1	+ 0.8	+ 1.0	+ 0.4	—0.6	+ 0.3	+ 1.2	+ 1.0
—1.1	+ 0.7	—0.4	—1.0	+ 0.8	—0.2	+ 0.5	—0.8	—0.5	—0.5	—
—1.2	—1.5	—1.5	—1.0	+ 1.0	+ 0.1	—0.2	+ 0.4	—0.7	—1.0	—
—1.1	—1.5	—1.2	—0.9	+ 0.6	—0.3	—1.1	+ 0.3	—1.0	—1.3	—
—1.7	—1.3	—1.9	—1.0	—0.4	+ 0.5	+ 1.3	—1.0	+ 0.2	—0.4	—
—0.5	—1.2	—1.3	—0.9	—0.7	+ 2.0	+ 1.5	—0.2	—0.1	—1.0	—
—0.1	—0.7	0.0	+ 0.6	—0.5	—0.5	+ 0.7	+ 1.0	+ 0.7	+ 0.6	—
+ 0.8	0.0	—0.4	+ 0.8	—0.1	+ 1.5	+ 1.3	+ 0.4	+ 1.5	+ 1.9	—
+ 1.5	+ 0.2	—1.2	+ 1.0	+ 0.5	+ 0.8	+ 0.9	+ 1.0	+ 1.0	+ 1.6	-

ments at Horta, in the Azores, the interpretation of the results was more complex. In the measurements made on the other cables the chief feature is a solar fluctuation. Thus, for example, the Horta-St. Vincent potential difference is at a maximum near local noon, and there is another much weaker maximum near midnight. This feature is a very common one on the North-South components of the potential gradient associated with earth currents measured at continental earth current observatories and is not connected with deep sea tides (ROONEY, 1939). If an average of this solar variation is obtained over seven days and then this hourly solar average is subtracted from each observation the residual curve, when plotted, shows a pronounced semidiurnal lunar period which can be seen by eye. In order to obtain the mean amplitude and phase of the semidiurnal lunar component, an average of the residuals for each lunar hour is computed. The data have not been subjected to any more sophisticated harmonic analysis because the duration of each series of observations is quite short by earth current observatory standards. On the other hand, the duration is quite long by oceanographic anchor station standards.

The use of tidal elevations to obtain indirect information about the tidal currents is not so simple in the case of these sections. DEFANT (1932)

Table III. *Horta-Saint Vincent Potential Difference (volts).*

GMT	June 20	21	22	23	24	25	26	27	28	29	30	July 1
0000	—	—0.8	—0.2	—0.2	—0.2	—0.4	+0.2	0.0	+0.2	0.0	0.0	—1.2
0100	—	—0.8	—0.4	—0.4	—0.4	—1.0	+0.2	0.0	+0.6	+0.6	—0.6	+0.4
0200	—	—1.0	—0.8	—1.2	—0.8	—1.4	—0.4	—0.2	+0.4	0.0	+0.2	+0.2
0300	—	—1.2	—0.8	—1.0	—1.4	—1.6	—0.6	—0.4	+0.4	—0.4	+2.0	+0.2
0400	—	—0.6	—0.8	—1.0	—1.6	—1.4	—0.6	—0.8	—0.4	—0.8	+0.6	+0.2
0500	—	—0.3	0.0	—0.6	—1.6	—1.4	—0.6	—1.2	0.0	—1.0	+1.4	+0.2
0600	—	—0.3	—0.8	—0.2	—0.8	—0.6	—0.8	—1.4	—0.2	—1.2	+1.0	+0.2
0700	—	+0.2	—0.4	—0.2	—0.6	—0.6	—0.6	—1.2	—1.6	—2.0	—0.2	—1.6
0800	—	0.0	—0.4	—0.4	0.0	—0.6	—0.6	—1.2	—1.6	—3.0	—3.0	—2.2
0900	—	+0.2	0.0	0.0	+0.2	—0.2	0.0	—0.6	—1.2	—3.2	+0.3	—0.6
1000	—	+0.8	+1.2	+1.0	+1.2	+1.4	+1.0	+0.6	+0.2	+0.6	—0.6	—1.6
1100	—	+1.0	+1.2	+1.8	+2.2	+2.4	+2.4	+2.0	+2.0	+3.0	—0.6	—1.0
1200	—	+1.0	+1.8	+1.6	+2.4	+2.4	+3.0	+3.0	+3.6	+2.2	+0.6	+2.2
1300	+1.8	+1.0	+2.0	+1.6	+2.0	+2.2	+2.8	+3.2	+4.8	+3.2	+2.0	+2.2
1400	+2.5	+0.2	+0.6	+1.2	+0.4	+1.4	+1.8	+3.2	+4.2	+5.8	+3.4	+2.6
1500	+2.2	+0.4	+1.4	+0.4	+0.8	+1.4	+0.6	+2.2	+2.0	+2.2	+3.8	+2.8
1600	+2.2	+0.6	0.0	+0.6	+0.4	+0.4	—0.2	+0.8	+0.8	+1.2	+2.0	+2.0
1700	+2.6	+1.2	—0.2	+0.2	+0.6	—0.2	—0.6	—0.2	—0.4	0.0	+0.4	+1.2
1800	+2.4	+1.0	0.0	+0.6	+0.6	—0.6	—0.6	—1.0	—1.2	—0.4	—1.0	+0.6
1900	+1.8	+0.4	—0.4	0.0	+0.6	—0.6	—0.4	—2.0	—1.6	—2.0	—1.8	—
2000	—0.8	—1.0	0.0	—0.4	—1.0	—0.2	—0.8	—2.2	—1.6	—2.6	—3.2	—
2100	—3.6	+0.6	+0.4	0.0	—0.2	—0.2	—0.8	—2.2	—1.2	—3.0	—2.8	—
2200	—3.0	—1.4	—0.6	—0.2	+0.6	+0.4	0.0	—3.0	—0.6	—3.0	—2.0	—
2300	—2.6	—0.2	—0.4	—0.4	0.0	+0.2	0.0	0.0	0.0	—0.4	—0.6	—

has developed a tidal theory for the Atlantic Ocean which fits the observed phases and amplitudes of the semidiurnal tide at islands along the middle of the ocean. A comparison of the equivalent infinite channel velocity on the Horta-St. Vincent section with the tidal current from Defant's theory leads to results similar to those obtained on the Halifax-Bermuda-Turks Island section. Between St. Vincent and Horta the tide is apparently essentially a progressive wave moving in from the South Atlantic Ocean, and from Defant's tidal theory one would expect Horta to be most positive with respect to St. Vincent at 1 hr. Greenwich lunar time, the mean tidal velocity being 1.2 cm/sec. The electrical measurements yield 0 hrs. Greenwich lunar time, and an equivalent infinite channel velocity of 1.0 cm/sec.

To the west and north of Horta the character of the tide becomes more complex. Sterneck (Defant, 1932) has drawn a large amphidromic system in this area. The velocities and phases obtained from Defant's theory do not agree well in this area with the equivalent infinite channel velocities on either the New York-Horta or Horta-Porthcurno sections. In both cases the electrical signals are unaccountably weak. There have been so many approximations made in the reasoning leading up to these

Table IV. *Horta-Porthcurno Potential Difference (volts).*

GMT	June 21	22	23	24	25	26	27	28	29	30	July 1
0000	—	+ 0.2	—0.2	+ 0.8	+ 0.4	+ 0.2	+ 0.8	+ 0.2	—0.2	—0.2	—0.4
0100	—	—0.4	0.0	—0.2	0.0	+ 0.2	+ 0.2	+ 0.2	—0.2	—0.8	—0.6
0200	—	—0.4	0.0	0.0	+ 1.0	+ 0.4	+ 0.6	+ 0.2	—0.2	—1.2	—0.8
0300	—	—0.4	0.0	+ 0.4	+ 0.8	+ 0.4	+ 0.4	+ 0.6	0.0	+ 2.4	—0.4
0400	—	—0.4	+ 0.4	—0.2	0.0	+ 0.2	+ 0.2	—0.2	+ 0.2	+ 2.0	+ 0.6
0500	—	—0.4	+ 0.2	+ 0.8	0.0	0.0	0.0	+ 0.2	+ 0.6	—0.4	—0.4
0600	—	0.0	+ 0.2	+ 0.6	+ 0.2	—0.2	0.0	+ 0.4	+ 0.2	+ 0.8	—0.4
0700	—	—0.6	+ 0.2	—0.2	+ 0.2	—0.2	0.0	0.0	0.0	—0.6	+ 0.8
0800	—	0.0	+ 0.2	—0.2	0.0	—0.2	+ 0.2	0.0	+ 0.2	—0.6	+ 1.0
0900	—	+ 1.4	+ 0.2	0.0	+ 0.4	—0.4	+ 0.2	0.0	+ 2.6	—0.2	+ 1.0
1000	—	—0.4	+ 0.4	+ 0.2	0.0	0.0	—0.6	+ 0.2	+ 2.2	+ 1.4	+ 0.8
1100	—	—0.6	0.0	0.0	—0.2	+ 0.4	—0.4	0.0	—2.0	+ 0.2	+ 2.2
1200	+ 0.8	+ 1.0	—0.4	—0.4	—0.4	—0.4	0.0	—0.6	—1.8	+ 0.4	+ 1.6
1300	0.0	—0.4	+ 0.2	—0.4	—0.6	—0.4	+ 0.2	—0.2	—0.8	0.0	—2.4
1400	—0.4	+ 0.8	—0.2	0.0	—0.8	—0.4	—0.2	—0.4	—1.8	—0.4	—0.8
1500	—1.0	—0.8	—0.2	—0.2	+ 0.2	—0.8	—0.4	—0.2	+ 2.2	+ 1.6	0.0
1600	—0.8	—1.4	—0.8	—0.2	0.0	—0.8	0.0	—0.4	+ 1.2	—	—1.0
1700	—0.8	—	—0.8	—0.2	—1.0	—1.2	—1.0	—0.4	+ 1.2	—	+ 0.8
1800	—2.0	—	—0.8	—1.4	—1.0	—1.2	—0.8	—0.2	—1.0	+ 2.8	+ 0.4
1900	—1.4	—0.4	—0.4	—1.4	—1.0	—1.4	—0.8	—1.0	+ 1.4	—2.2	—
2000	+ 0.8	—0.8	+ 0.2	+ 0.6	—0.2	—0.8	—0.6	—1.0	—0.6	—1.6	—
2100	0.0	—0.4	+ 0.2	—0.4	+ 0.2	—0.4	—1.0	—1.0	+ 2.8	—0.4	—
2200	0.0	—0.6	+ 0.8	+ 0.6	+ 0.4	0.0	—1.0	—0.4	+ 0.2	+ 1.2	—
2300	+ 1.0	+ 0.8	+ 0.8	+ 0.6	0.0	—0.6	+ 1.0	—0.4	+ 0.2	—0.2	—

discrepancies, that one would be reckless to pursue the matter further. It would be interesting, however, to see whether alternative cotidal charts might be drawn which agree better with the electrical data. Up to this point no mention has been made of the data obtained from serial current observations at anchor stations.

V. Comparison with anchor station data.

The most up-to-date summary of the results of anchor stations in the North Atlantic is that given by von Schubert (1944) in his report on the two last Meteor anchor station data. Most of the anchor stations in the North Atlantic were occupied for a very short time, or were made so near to the coast as to be of doubtful applicability to the deep ocean, or else the measurements were confined to only the upper layers. In the case of the section between New York and Horta there are three anchor stations near enough to the section to permit comparison with the equivalent infinite channel velocity. The semidiurnal tidal component of current observed at these stations was used to compute the velocity normal to each section and the Greenwich lunar time of maximum flow.

Table V. *Horta-Halifax Potential Difference (volts).*

GMT	June 25	26	27	28	29	30	July 1
0000	—	— 0.4	+ 0.6	— 0.4	+ 0.6	+ 0.4	— 0.4
0100	—	0.0	+ 1.4	— 0.4	+ 0.2	0.0	— 0.2
0200	—	0.0	+ 0.4	— 0.4	+ 0.2	— 2.8	— 1.0
0300	—	0.0	+ 0.2	+ 0.4	+ 0.4	— 2.0	— 1.2
0400	—	+ 0.2	0.0	— 0.2	+ 0.4	— 2.4	— 1.8
0500	—	0.0	— 0.2	+ 0.2	+ 0.2	— 0.2	— 2.4
0600	—	0.0	0.0	+ 0.2	+ 0.4	— 2.6	0.0
0700	—	0.0	+ 0.2	+ 0.4	+ 0.6	+ 1.2	+ 0.2
0800	—	0.0	+ 0.4	+ 0.6	+ 1.6	— 2.8	+ 0.8
0900	—	— 0.4	— 0.2	— 0.2	— 1.2	— 1.0	— 0.6
1000	—	— 1.4	— 1.0	— 1.0	— 5.2	— 1.0	+ 0.4
1100	—	— 1.8	— 1.6	— 2.4	— 1.2	— 1.6	— 3.2
1200	—	— 1.8	— 2.4	— 3.4	— 2.4	— 2.0	— 2.2
1300	— 0.4	— 1.2	— 2.6	— 3.2	— 3.4	— 2.0	— 0.4
1400	— 0.2	— 0.8	— 2.0	— 1.4	— 6.0	— 2.0	— 0.4
1500	+ 0.8	— 0.6	— 2.2	— 0.2	— 0.2	— 3.0	— 1.4
1600	+ 1.8	+ 2.0	+ 0.8	+ 1.6	+ 1.6	—	— 0.6
1700	+ 2.4	+ 2.4	+ 1.8	+ 3.2	+ 3.6	—	+ 0.6
1800	+ 2.4	+ 4.0	+ 3.6	+ 2.8	+ 3.4	+ 1.0	+ 1.6
1900	+ 2.2	+ 4.2	+ 3.8	+ 3.4	—	+ 1.2	—
2000	+ 1.2	+ 3.2	+ 3.8	+ 2.6	+ 3.0	+ 0.8	—
2100	— 0.2	+ 1.8	—	+ 1.6	+ 1.4	+ 1.4	—
2200	— 1.2	+ 0.6	+ 1.2	+ 0.2	+ 1.0	— 0.2	—
2300	— 1.0	+ 1.2	— 1.0	+ 0.8	+ 0.4	— 0.4	—

The tidal velocities obtained from anchor stations are from two to ten times greater than those obtained from DEFANT's tidal theory, which in turn are ten times greater than those indicated electrically. Between Horta and St. Vincent there are two anchor stations, each of which yields tidal velocities ten times those indicated by tidal theory and electrically.

VI. Conclusion.

In summary, then, one can make the following remarks regarding these measurements: the observed lunar semidiurnal component of electrical potential difference between Halifax and Turks Island, and also between Horta and St. Vincent agrees with what would be expected from the tidal currents deduced from existing tidal theory in the North Atlantic. In these two cases the conductivity of the bottom appears to be low enough to have little short circuiting effect. An exact comparison is not possible because of the lack of a theory taking into account the complex geometry of the ocean basin. On the cables from New York to Horta, and Horta to Porthcurno the voltages measured are much less than anticipated from tidal theory. It is possible (but not in any

Table VI. *Comparison of Various Indications of Semidiurnal Tidal Current.*

Points of measurement	Electrical data			Theoretical tidal current		Method	Tidal components of nearby anchor stations			
	Semi-diurnal potential (volts)	G. L. T. of max. pot. (hrs.)	Velocity in equivalent infinite channel (cm/sec)	G. L. T. of max. velocity (hrs.)	Velocity (cm/sec)		Station	Depth (meter)	Velocity component normal to section (cm/sec)	G. L. T. of max.
(1)	(2)	(3)	(4)	(5)		(6)	(7)	(8)	(9)	(10)
Halifax-Turks Is. Mean $H_z = 0.47$ Distance between 2800 km	1.2	3	0.9 E	3	1.2	Standing wave theory gives mass transport across Halifax-Turks Is. line	None			
New York-Horta Mean $H_z = 0.47$ Distance between 3500 km	0.4	11	0.24 N by E	1	2.5	DEFANT's 1933 tidal theory of N. A. tides. Section 11	Michael Sars 58	15	24	11
							Meteor 438	300 — 800	5	4
							Altair	300 — 800	7	0
Horta-St. Vincent Mean $H_z = 0.29$ Distance between 2000 km	0.6	0	1.0 E by N	1	1.2	DEFANT 1933, Section 16, amplitude reduced by 0.5 times because of stream ellipse eccentricity. Phase of E by N direction of flow	Armauer Hansen E	300 — 1000	10	2
							Meteor 214	100 — 1000	10	11
Horta-Porthcurno Mean $H_z = 0.41$ Distance between 2000 km	0.4	2	0.5 NNW	0	2.6	DEFANT 1933, Section 6, amplitude reduced by 0.8 times. Phase of NNW direction of flow	None			

sense proved) that the discrepancy is due to inadequacies in the tidal theory. Finally, neither tidal theory nor electrical measurement agree with the few observations made at anchor stations.

Acknowledgments.

The cable between New York and Horta belongs to the Western Union Telegraph Company, the cables between Halifax, Bermuda, Turks Island, Horta, St. Vincent, and Porthcurno to Cable and Wireless Ltd; it scarcely needs to be said that I could not have made these measurements without the generous cooperation of these two companies. I have had an enormous amount of assistance and advice from the local managers, engineers and their staffs. In particular I am indebted to Mr. J. A. Smale, Engineer-in-Chief of Cable and Wireless Ltd, and Mr. C. S. Lawton, General Plant Engineer of Western Union Telegraph Company.

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Three Detailed Cross-Sections of the Gulf Stream.[1]

By L. V. WORTHINGTON, Woods Hole Oceanographic Institute

(Manuscript received 29 January 1954)

Abstract

Three sections across the Gulf Stream in which deep temperature and salinity observations were made close intervals show that comparably large values of surface current velocity are obtained from at dynamic computations, the Geomagnetic-Electrokinetograph (G.E.K.) and from navigational data. The dynamic computations indicate that the crosscurrent slope of the isobaric surfaces is uneven, resulting theoretically in three or four zones of high velocity separated by zones of lower velocity. The navigational and GEK measurements do not clearly reflect this picture. It is suggested that the unevenness of the slopes of the isobaric surfaces is related to the surface temperature discontinuities observed in the Gulf Stream by von Arx and RICHARDSON (1953) from aircraft, and that the Stream is composed of overlapping, discontinuous currents at all levels.

Introduction

With the advent of Loran and GEK equipment it became possible to measure the velocity of surface currents from a moving ship with some accuracy. In the Gulf Stream velocities of 4 to 5 knots (200 – 250 cm/sec) were normally found by Loran in the swiftest part of the current (ISELIN and FUGLISTER 1948). VON ARX (1950) measured a peak velocity of 274 cm/sec with the GEK and values of more than 200 cm/sec are commonly observed with this instrument.

These velocities were in excess of those previously found by Dynamic Computations, a previous maximum being 140 cm/sec (SEIWELL 1939, Fig. 19) in a typical section from Montauk Point to Bermuda. ISELIN and FUGLISTER (1948) pointed out that values obtained by means of the geostrophic equation in the period 1931 – 1940 must be regarded as minimum values since the stations were usually too widely spaced to observe the true slopes of the isobaric surfaces. Also, with the navigational equipment available during that period it was impossible to tell at what angle to the Stream a section was made. If this angle were to deviate more than about 10° from the perpendicular a noticeable reduction in computed velocity would result, since the computations are concerned only with the component at right angles to the sections.

A cruise was made in the ATLANTIS in October and November 1950 in which the primary objective was to make sections across the Stream in which the slopes of the isobaric surfaces would be closely observed. This involved making hydrographic stations, consisting of serial observations of temperature

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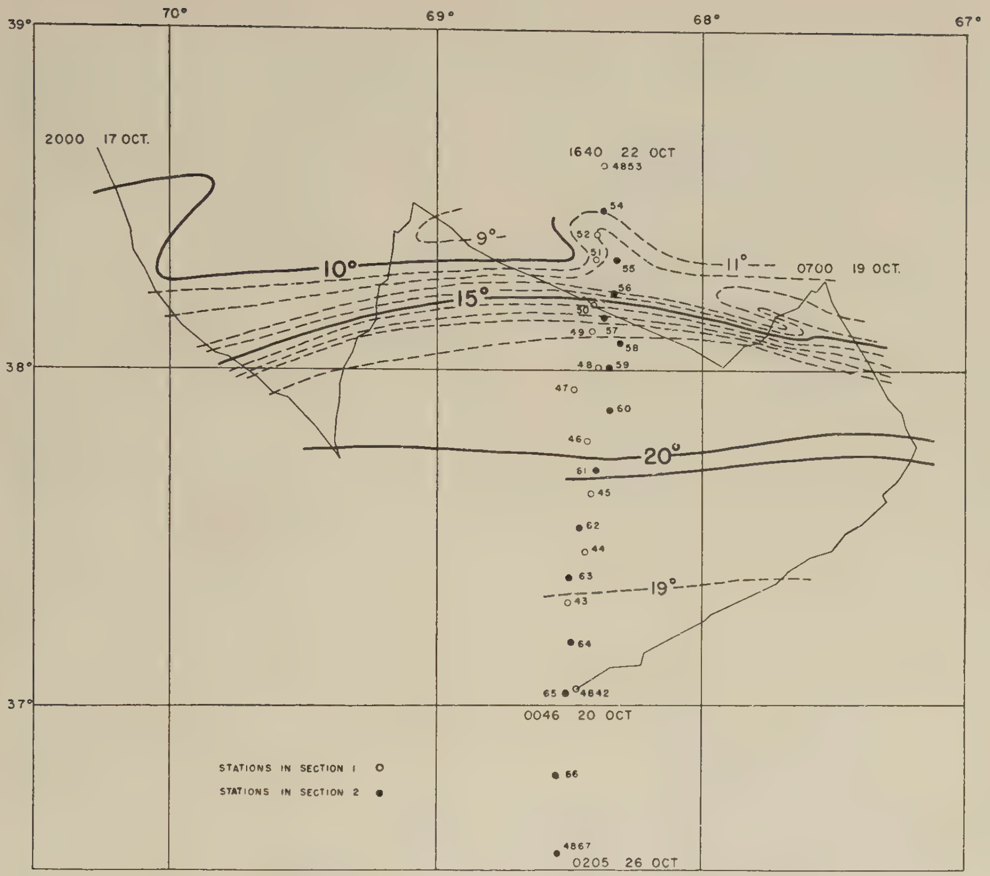

Fig. 1. Temperature at 200 m during preliminary survey and section 1.

and salinity, at closely spaced intervals across the current and at right angles to its axis. Without Loran, which enables the observer to fix the ship's position as frequently as he desires, this program could not have been attempted. It was planned to measure the surface current between stations with the GEK and Loran and to arrive at a proper basis for comparing the values obtained by these instruments with those computed from the temperature and salinity data.

The Sections

A preliminary survey was made to establish the location and curvature of the Stream. The results of this survey and the placings of the first two sections are shown in Figure 1. The contours of 200 m temperature are usually considered an adequate index of the location of the Stream (FUGLISTER 1951). The placing of Section 1, stations 4842 – 4853, was decided on the basis of this survey. Section 2, stations 4853 – 4867, was made immediately afterwards on a reversed course since negligible changes in the position of the Stream had taken place between the time of the survey and the time when Section 1 was completed.

Four days elapsed before Section 3 was made and no time was available for another survey. Consequently the placing of Section 3 was decided on the basis of a single crossing of Stream. This resulted in Section 3's not being made at right angles to the current since the Stream had meandered during the four days in a manner not recognized by the

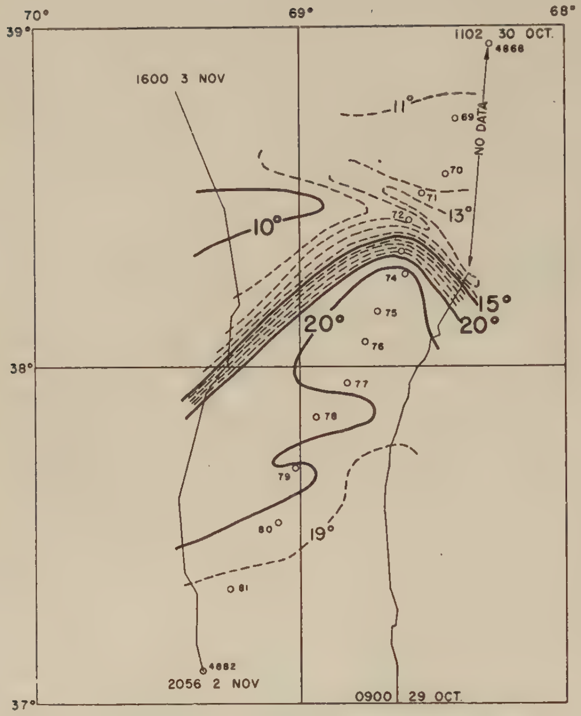

Fig. 2. Temperature at 200 m before, during and after section 3.

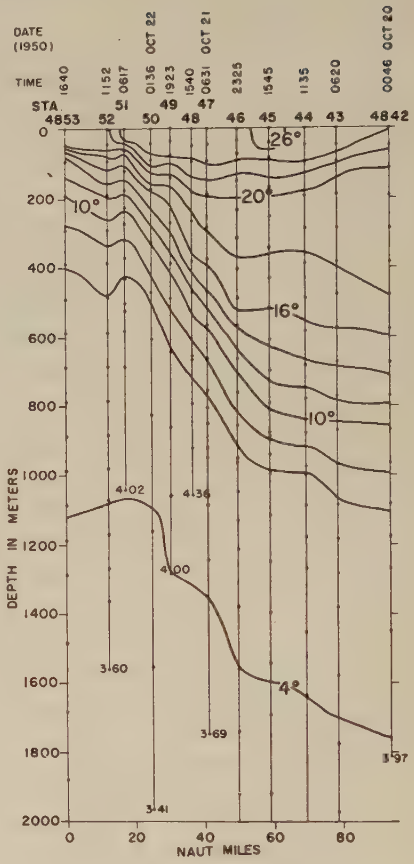

Fig. 3. Section 1:Temperature.

observers. Figure 2 shows the location of Section 3, the crossing (29 – 30 Oct.), on the basis of which the location was chosen, and the contours of 200 m temperature before, during and after the section. GEK current direction data indicate that Section 1 deviated 2° from the perpendicular to the axis of the Stream, Section 2 four degrees and Section 3 sixteen degrees. (The axis of the Stream was considered to be the average direction of those GEK current fixes with velocities of more than 100 cm/sec in each section.)

The temperature profiles of the three sections are shown in Figures 3, 4, and 5, together with the distribution of the data, each dot representing an observation of temperature and salinity. Salinity profiles are not presented here since the T/S relationship was consistent, except in very shallow (0 – 200 m) observations close to the inshore edge of the current.

In general two series of eleven Nansen bottles each used, the shallow series from 1 to 900 m and the deep from 1,000 to 3,200 m by wire. Large wire angles were encountered, particularly in Section 1 where no efforts were made to reduce them by maneuvering the ship. In the second and third sections, where the ship was maneuvered, the bottles reached a depth of more than 2,000 m on all of the stations but one. Five unprotected thermometers were usually used with each series and much confidence is placed in the accuracy of the bottle-depth determinations.

The station positions given in Figures 1 and 2, and the times given in Figures 3, 4, and 5 are those of the shallow series which usually reached a depth of 600 – 800 m. A Loran fix was obtained at the time the messenger was sent on each series. These sections are the most closely spaced available in the Gulf Stream, the usual distance between stations in the past having been about 20 nautical miles.

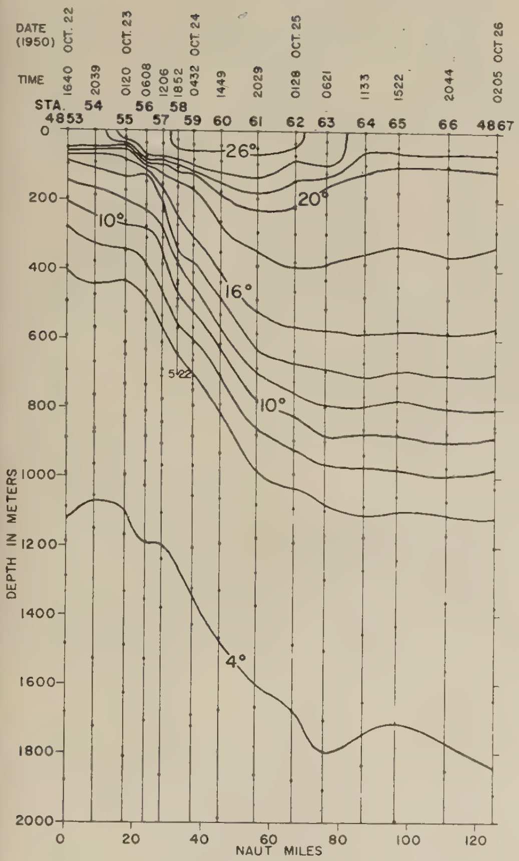

Fig. 4. Section 2:Temperature.

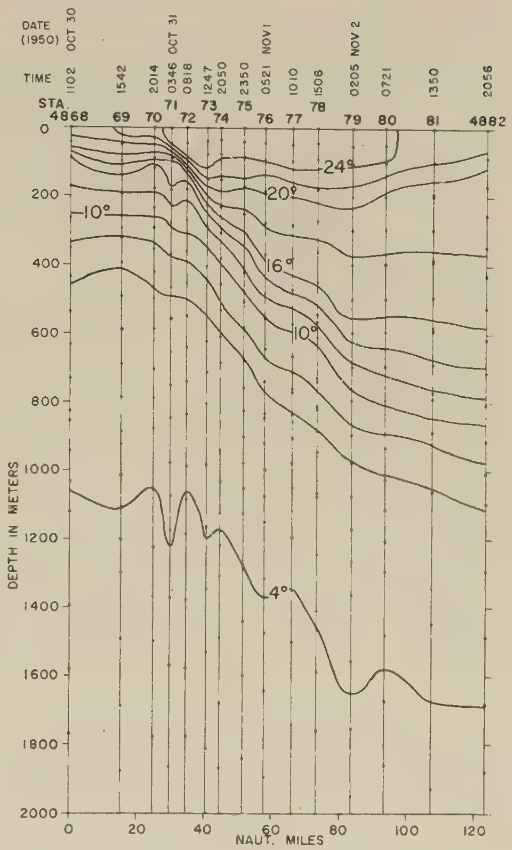

Fig. 5. Section 3:Temperature.

The Dynamic Computations

In all important particulars, the method of computation described by LA FOND, (1951) has been used. The major source of inaccuracy in dynamic computations lies in the fact that small errors in position may give erroneously steep or gentle slopes to the isobaric surfaces, resulting in large errors in the computed currents. VON ARX (1952) has estimated that Loran fixes have an average error of 1 km., (about 0.5 nautical miles) in this area. Since Loran fixes were usually obtained at half-hourly intervals during these sections this error should give a scatter of ± 1 knot (about 100 cm/sec) in the values of current velocity obtained by this means. The observed scatter was considerably smaller than this which leads one to suspect that von Arx's estimate is pessimistic. However, in presenting the computed surface currents graphically (Figs. 6, 7, and 8) the effect of an 0.5 nautical miles error in the position of each station has been plotted as an envelope around the curves of surface velocity derived from the computations.

The true distances between stations were not used in all cases since many stations fall up or downstream from a mean line drawn through them. Instead it was assumed that all stations fall on the mean line.

The computed velocities are based on the assumption of a level of no motion at 2,000 m. This level was chosen because nearly all the stations extended to that depth, and the errors involved in the choice of this level are small. In Sections 2 and 3 data were available down to 3,000 m. These data show that a 5 % increase in computed volume results if the 3,000 decibar surface is assumed to be motion-

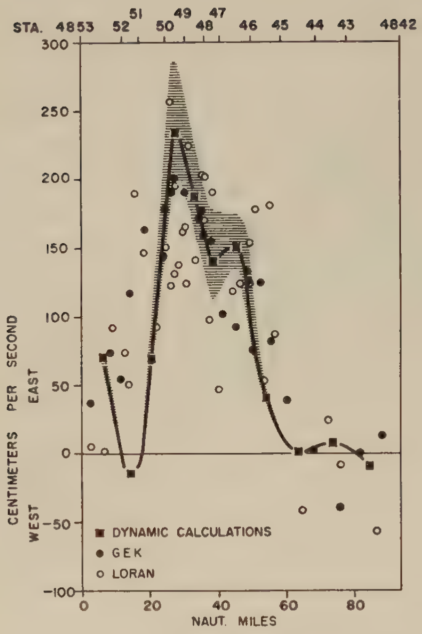

Fig. 6. Surface velocity—section 1.

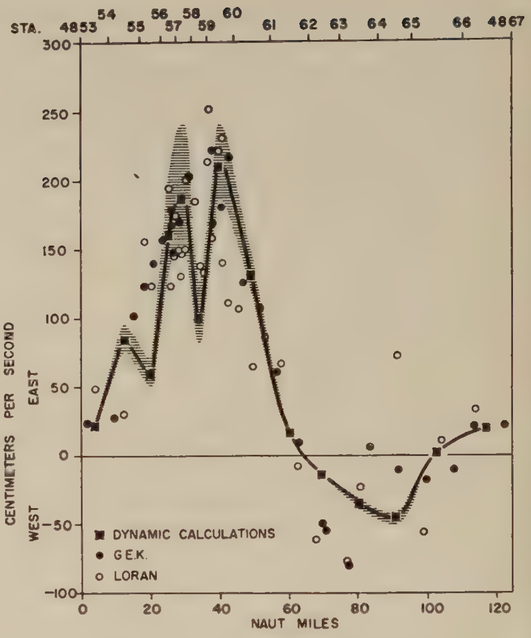

Fig. 7. Surface velocity—section 2.

less instead of the 2,000 decibar surface. Calculated velocities at 2,000 m referred to the 3,000 decibar surface average, 3.5 cm/sec in Sections 2 and 3. This figure is approximate since the errors of salinity analysis (reckoned at ± 0.02 %) are critical at these depths.

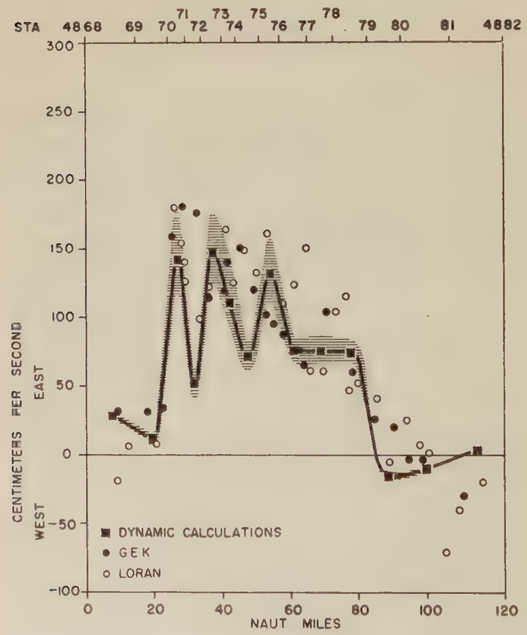

Fig. 8. Surface velocity — section 3.

Current Measurements by GEK

Current fixes were obtained with the GEK as frequently as time allowed when steaming between stations. The measured currents have been increased by a *K* factor of 1.2 (VON ARX 1950). This *K* factor is an empirical factor based on all the comparisons between currents measured with Loran and those measured with the GEK on this cruise, in which the GEK on average gives lower values than Loran.

More GEK measurements would have been desirable but they were sacrificed, perhaps too freely, in order that the ideal synoptic section might be more closely approached. About 25 measurements were made with each section.

Current Measurements by Loran

Loran fixes were obtained at half-hourly intervals when underway and the currents calculated according to the ship's displacement from its dead reckoning positions. The effect of wind drift was ignored. The errors in the

Loran positions have been discussed above. About 35 current measurements were made with Loran in each section, and the component values at right angles to the sections used for comparison with the dynamic values.

The Comparisons

The three surface velocity profiles show that comparable values are found with all three methods of measurement, but the dynamic calculations indicate an unevenness of structure that is not clearly shown by the other two methods. To be sure, the Loran gives a more uneven picture if all the positions are assumed to be exact but the scatter of the Loran points is ascribed here, as elsewhere, to unavoidable errors in the system.

In all three sections the geostrophic equation consistently argues that the Stream is composed of bands of swift moving water separated by bands of relatively slow moving water. The navigational data are sufficiently accurate to ensure that large changes in the cross current slopes of the isobaric surfaces are real. What is not clear is whether or not there is a sufficiently close relationship between the slopes of the isobaric surfaces and the surface currents to warrant the assumption that the cross-current profile presented by the dynamic computations is more correct than those presented by Loran and GEK.

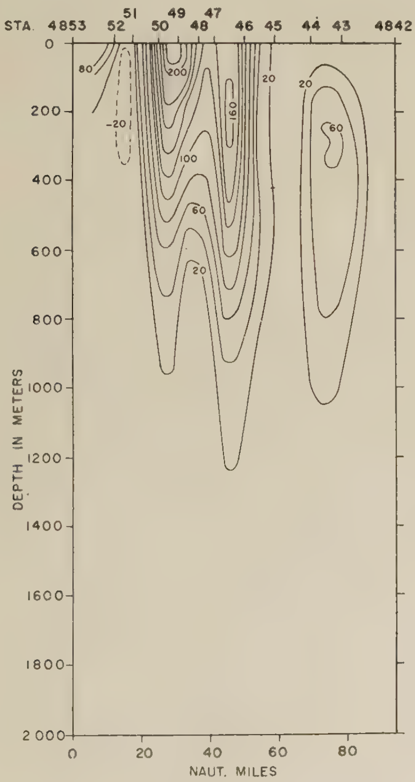

Fig. 9. Section 1—velocity cm/sec.

The dynamic computations ignore the effect of frictional forces which would tend to smooth out the unevenness required for a steady state. It is further possible that local winds and waves have a like effect on the surface layer. On the other hand the high scatter of the Loran measurements may obscure unevennesses in the currents that actually exist, and recent work by Longuet-Higgins, Stommel and Stern (not yet published) indicates that GEK values are influenced by the motion, or lack of motion, of water at some distance from the point of observation. The effect of this would certainly be toward averaging out the high and low velocity zones in these sections.

It is worthy of note that the existence of such high and low velocity zones was not suspected by the observers in the ship even though continuous temperature profiles were kept up as the station data came in. The changes in the slopes of the isotherms were regarded as negligible except in cases near the northern edge of the Stream where the slopes were actually reversed.

In retrospect, looking through past bathythermograph profiles across the stream where the 900 foot instrument was used, it was seen that changes in the slopes of the isotherms at the 200 m level, comparable to the changes found in these sections, are the rule rather than the exception. These bathythermograph data were obtained from ships continuously under way, which implies that the changes in slope found in these three sections cannot be attributed solely to the long time lapse between stations, and that comparable changes would have been found if all the stations in a section had been occupied simultaneously.

Subsurface Currents

From the computed velocity profiles illustrated in Figures 9, 10, and 11 it can be seen that the unevenness of the Stream is not confined to the surface layers. If the unevenness

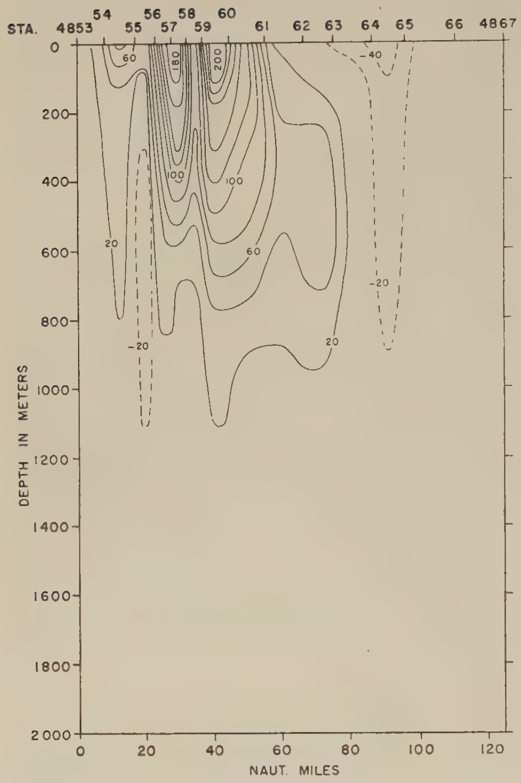

Fig. 10. Section 2—velocity cm/sec.

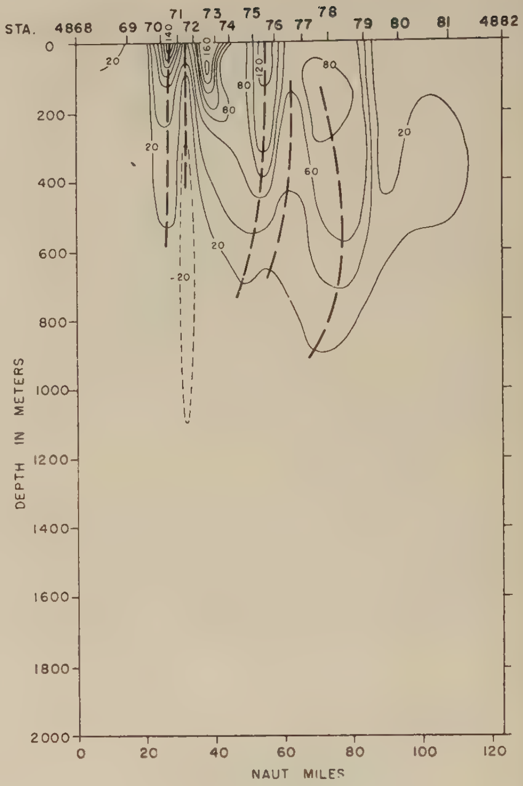

Fig. 11. Section 3—velocity cm/sec.

were due to errors in navigation one would expect that a high or low velocity zone would be found at all depths between the same pair of stations. In Figure 11 dashed lines have been drawn through the high and low zones, and it can be seen in many cases that a high zone at the surface is over a low zone at mid-depths.

In Section 3 (Fig. 11) the Stream appears to be divided into three parts, the two major parts being separated by a deep countercurrent. It is tempting to conclude that here the Gulf Stream is moving laterally across the countercurrent by re-forming to the north, and that the low velocity zones found further towards the southern edge of the Stream are the remnants of countercurrents which have been absorbed into the main current in the same manner, further upstream. Such crossings do not imply that Slope water is moving across the Stream but that changes in the slopes of the isobaric surfaces move slowly across the Stream in a manner analogous to wave motion.

Recent studies using aircraft (von Arx and Richardson 1953) have shown that on the surface the Florida Current and Gulf Stream fronts are discontinuous. Using the Stommel-Parson airborne radiation thermometer they found that surface temperature gradients associated with the front diminished in a downstream direction to the point where they could no longer be detected, but that by turning to the left a fresh gradient could be found which in its turn would fade out. These three cross-sections suggest that these discontinuities are not merely surface phenomena but that the Gulf Stream is discontinuous at all levels all the way across its width. More accurate direct current measurements are necessary to determine to what extent the velocity pattern is a part of these discontinuities in the pressure field.

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Contribution No. 695

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LETTERS TO THE EDITORS

A correlation between the oxygen content of sea water and the organic content of marine sediments*

THERE is considerable opinion but little direct evidence that the oxygen content of overlying water masses is important in determining the organic content of marine sediments (CORRENS 1939 ; FLEMING and REVELLE 1939).

CORRENS (1939) noted a very general inverse relationship in the *Meteor* observations, and concluded that the high oxygen content of the Atlantic deep water was not favourable to the preservation of the organic matter in the sediments. On the other hand, he stated in 1937 " Vergleicht man nun die Sauerstoffwerte des Tiefenwassers . . . . mit dem Humusgehalt der Sedimente, so findet man keine Parallelität." KUENEN (1942) found no direct correlations between these variables in the Dutch East Indies.

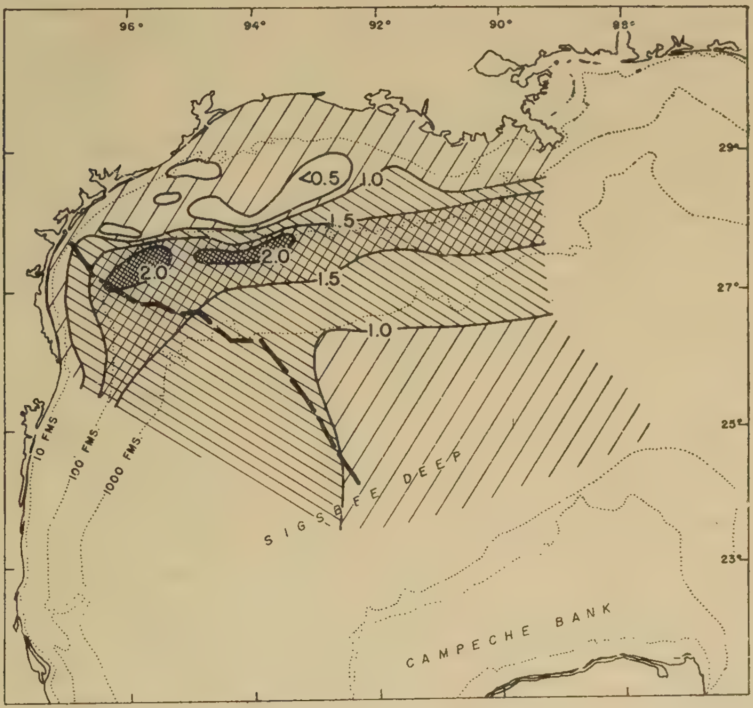

Fig. 1. Organic content of surface sediments. Numbers represent percent of organic matter, estimated as 1·8 times the carbon content. From Trask (8). Heavy dashed line shows line of stations used for comparison with bottom oxygen content in Fig. 2.

Data now available from the northwestern Gulf of Mexico indicate a clear-cut inverse relationship between the organic content of the sediments and the oxygen content of the overlying waters. TRASK (1953) has reported on the organic content of sediments, and oxygen was determined during a cruise of the *Atlantis* in 1935 (Bulletin Hydrographique). TRASK found maximum organic matter in sediments at depths of 150 to 850 metres, and minimum concentrations of oxygen (less than 3·0 ml/l) were found overlying the bottom at these same depths. The zones of maximum organic content and minimum oxygen correspond well, and closely follow the edge of the Continental Shelf (Fig. 1 and overlay).

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*Contribution No. 695 from the Woods Hole Oceanographic Institution.

Two lines of stations from each of these cruises lay close enough together that the organic nitrogen and noncarbonate carbon content of the sediments can be compared with the oxygen content of the water over the bottom, estimated by extrapolating the station data (Fig. 2). The maxima in nitrogen and carbon coincide closely with the oxygen minima, and an inverse relationship holds both below and above the oxygen minimum layer. It can be concluded that the highest organic content is found in the zone where the oxygen minimum layer impinges on the bottom.

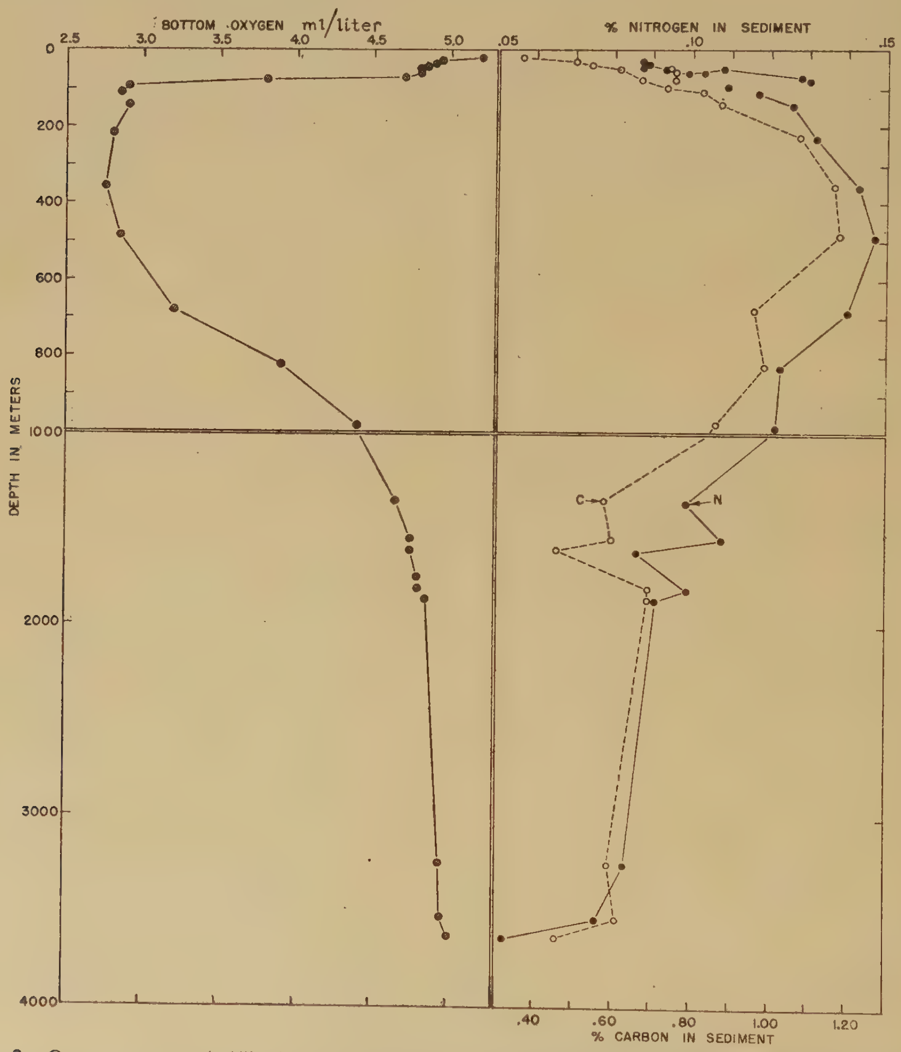

Fig. 2. Oxygen content (ml/litre) of water overlying the bottom and non-carbonate carbon content (%) and nitrogen content (%) of sediments along the lines of stations shown in Fig. 1 and overlay. Nitrogen estimated in surface layer of sediments, carbon estimated in layer approximately 25-35- cm. below the surface.

It may be predicted, from the oxygen distribution, that sediments rich in organic material will be found continuing northeastward from those reported by TRASK (Fig. 1), and along the edge of the Campeche Bank.

High organic content is equivalent to high oxygen demand, and so contact with organic-rich bottom sediments might be held responsible for the oxygen minimum. Such a mechanism was proposed by THOMPSON, THOMAS and BARNES (1934), and may cause the oxygen minimum layer which was observed off fjords by THOMPSON and BARKEY (1938). However, in the Gulf of Mexico, the oxygen minimum layer is presumably of more remote origin, representing waters de-oxygentated in the Atlantic Ocean. It is probable that in this region, the high organic content of the sediments is due to the presence of water of low oxygen content immediately above the bottom, and the smaller oxygen diffusion gradient available to provide oxygen to the subsurface layers of sediment.

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Contribution No. 696

OCEANOGRAPHIC INSTRUMENTS FOR MEASURING TEMPERATURE*

Allyn C. Vine

INTRODUCTION

A great deal of oceanographic effort in the past has gone into measuring ocean temperatures and determining how they vary with location, season and depth. For some problems, such as thermal flow, the measured temperature variations are the primary end. In other problems, temperature variations which are rather easy to measure give excellent correlation with some desired variable which is not easy to measure directly.

Temperature measuring equipment in oceanography has tended to be very simple for several reasons. First, the majority of the experimental oceanographers in the past were biologists rather than physicists or engineers. Secondly, when complicated apparatus was built and used, it usually either failed to work satisfactorily on shipboard or it would only work for the builder. Thirdly, the trend in almost any field work is to adopt the available instruments which give the least trouble and then they soon become the generally accepted instruments.

It is the purpose of this paper to describe some of the temperature measuring instruments which have been used, and the principal types of temperature measuring elements and systems. The principal effort, however, will be placed on trying to analyze the temperature problems we are confronted with, the limitations of present day instruments, and outlining new types of instruments that should be successful in attacking these problems.

OLDER INSTRUMENTS

Because of the relative ease of measuring temperatures compared to measuring salinity, density, or current, it has remained important not only as an end in itself but also as an indicator. It is presumed that this trend will continue and that temperature measurements will continue to be one of the most powerful and versatile ways we have of figuring out our oceanographic puzzle.

During the years we have gradually accumulated enough temperature measurements to obtain a rough overall picture of the northern Atlantic and Pacific which is reasonably descriptive for large scale phenomena. We are sadly lacking however to describe in a detailed way how thermal exchanges take place or to predict small scale oceanographic features.

Bucket and Thermometer - In order that this paper can have as simple a beginning as quantitative physical oceanography did, let us start out with the use of a bucket and a thermometer. The purpose of emphasizing such a simple piece of equipment is because much good work has been done with it. Bucket temperatures can be either correct or misleading depending upon the degree of thermal layering near the surface and depending upon the skill of the observer and interpreter. The simple bucket and thermometer will probably continue to be a mainstay for calibration purposes for a long time. In the hands of a good experimentalist it is also probable that good research work will be done with it in the future. For example, a modern version of the bucket is to use a hose and to pump water with it from a given depth to the surface.

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* - Contribution No. 696 from the Woods Hole Oceanographic Institution.

Water Intake Thermometers - Much of our knowledge of horizontal gradients in the ocean has come from a study of intake temperatures on ships. This has seldom given data which permits the study of fine horizontal structure but it would seem that this could and should be done. The sensitivity of the apparatus should be improved as well as the time constant. Practice has indicated that an observer usually has to go with the thermometer to insure that the necessary auxiliary data be obtained.

Reversing Thermometer - From 1870 until 1938 the two principal tools in physical oceanography were the reversing thermometer, to determine temperature, and the Nansen bottle to obtain water samples for salinity and oxygen determinations. This thermometer combined a simplicity of operation, a high absolute precision, and was operable over a wide depth range. Another excellent feature of the reversing thermometer is that when used in protected and unprotected pairs they constitute their own depth gage. These desirable characteristics have made it a standard oceanographic instrument and one which will not be entirely replaced in the forseeable future.

It does not seem necessary to describe the reversing thermometer in detail, as it is well known among oceanographers, and has been described several places in the literature. For the moment let us say that, under ideal conditions reversing thermometers can give temperature to about 0.02° C and depths to about 10 meters. The reversing thermometer, however, suffers from a slow speed of response and from being able to give data at only a limited number of depths.

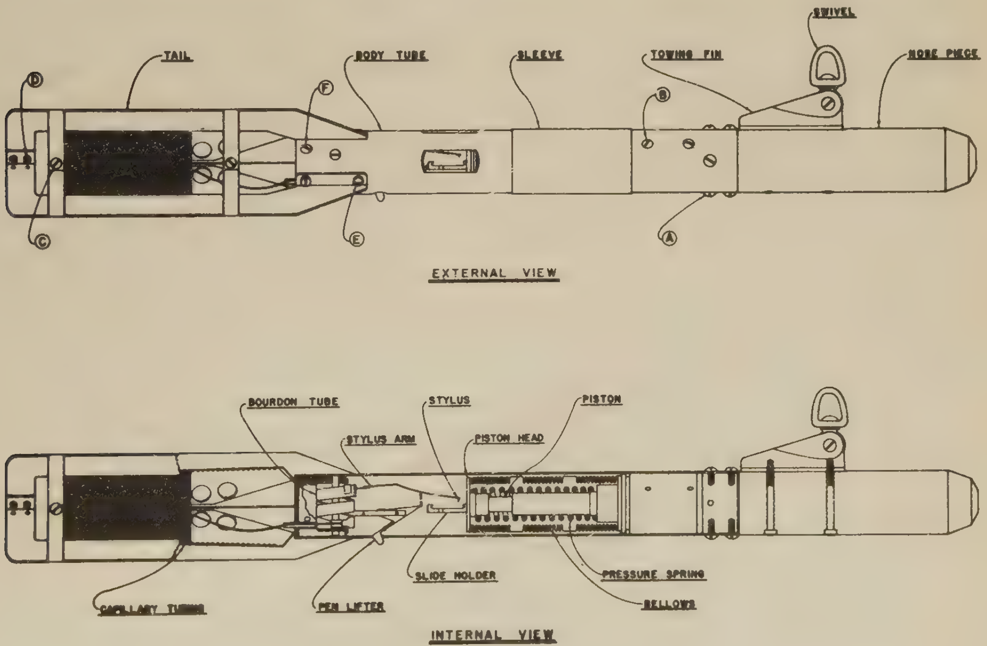
Because the reversing thermometer has become a standard tool in oceanography, it will pay us to critically examine its limitations so that we use them on experimental work for which they are best suited and do not improperly interpret results on experimental work for which they are unsuited.

Because of the nature of the use of reversing thermometers it is doubtful if they will ever be well suited for studying small scale or rapid thermal changes in the ocean. They are excellent, however, for studying the gross features of the ocean and for measuring stable temperatures at great depth. Another virtue of the reversing thermometer is that it has been paired for many years with the Nansen bottle and hence the general utility of each device is greatly enhanced by the presence of the other.

Bathythermograph - For many years there had been a need for a practical device which would make a continuous temperature measurement. In 1938 Spillhaus designed the bathythermograph which was an early practical temperature depth recorder. Furthermore, it was possible to use it from a slowly moving vessel.

In 1940 and 1941, Ewing, Worzel and the writer modified the bathythermograph considerably by adapting the Spillhaus instrument to be used as a diving instrument. The concept of towing a recorder at various depths was abandoned because of the heavy weight, cable and winch required. The emphasis was placed on redesigning the BT so that you dropped it overboard, paid out cable faster than the ship was going and let it fall free. The winch and cable were to retrieve the BT but were not designed to drag it at any appreciable depth and speed. This technique permitted measurements down to 400 feet at 12 to 15 knots on 1/16 inch steel cable, using a winch which only weighed about 300 pounds. It required that the BT be made to dive rapidly and that obtaining high speed of thermal response become the predominate design feature. The additional requirements of simplicity and freedom from vibration decided the choice of a liquid-filled bourdon temperature assembly, using some 50 feet of .020 inch bore by .050 inch O.D. Copper tubing for the thermal sensitive unit. The temperature bourdon was case-compensated with a bimetalic strip to reduce the thermal hysteresis of the instrument. With such a system the time for 90% response was decreased to about 4/10 seconds, or about 2/10 seconds to 1/e. Even this is none too good when the BT is dropping at 10 feet per second through a sharp thermocline.

The precision of reading the BT is from .1 to .3°F depending upon how fast the ship is going and on the adjustments of the pen. The depth accuracy is about 1% of full scale. The record is made on a 1 x 1 3/4 inch smoked microscope slide. While the record is small it is capable of being read as accurately as the data on it and it can readily be examined against a calibrated grid with either a 5 power eye piece or a projector. Figure 1 is a schematic of this instrument essentially as it is available on the commercial market.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STYLUS
PISTON
STYLUS ARM
PISTON HEAD
SLIDE HOLDER
PRESSURE SPRING
BELLOWS
CAPILLARY TUBING
PEN LIFTER
INTERNAL VIEW

Fig. 1. The Bathythermograph

While the BT is not a particularly complicated instrument its reliability and surprisingly accuracy have vastly increased our knowledge and appreciation of the complexity of the thermal structure of the ocean.

WHAT SHOULD WE MEASURE?

This section is aimed at showing what a large range of thermal measuring problems exist in the ocean and what a large variety of instruments will be required to solve them. It is also aimed at making us look more critically at the measurements which we take.

Figure 2 is an attempt to show that one can find thermal problems in the ocean of almost any linear dimension in depth one chooses. This figure indicates the various full scale depth ranges one might use for different problems. Figure 2 illustrates several features:

a. No matter what depth scale one chooses to work over there are other smaller scale phenomena and problems. There are also very apt to be larger scale phenomena.

b. An individual instrument will only cover a farily small range of depths, usually this is from full scale to 1% or possibly 1/10% of full scale. Because of this limitation many problems must be tackled with two or more types of instruments.

c. Attention is called to the logarithmic chart because it infers that the surface (zero depth) cannot be attained. The writer used to be worried about this aspect of logarithmic presentation but he is now convinced that this is an experimental reality with which we must live. The finite size of thermal probes, the characteristic infra red radiation methods, and the general oscillatory motion of the water surface make the true surface temperature something about which we can speculate but can probably never measure. This may seem like a trivial point but to study evaporation problems one may well want to know what is happening in the top few microns.

d. The fact that oceanography involves problems covering a full scale depth range of over 100,000,000 is something we should bear in mind when considering future research problems.

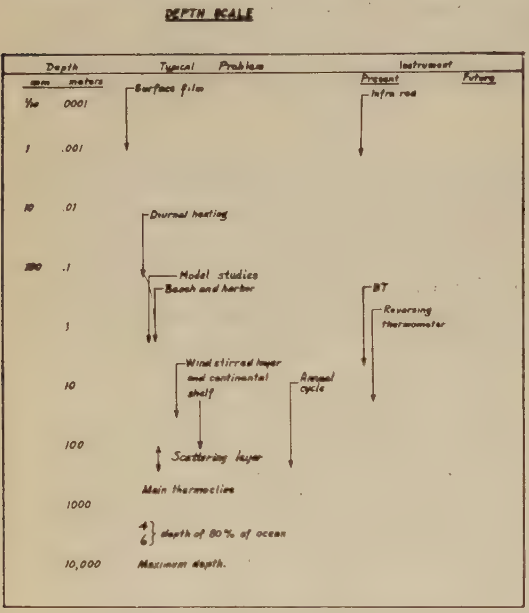

Fig. 2. Depth Scale

Any division into categories must necessarily be somewhat arbitrary but the writer also suggests the following breakdown of operating depth as the ones which usually affect pressure case design, length of cables, etc.

1. Above the water	Marine meteorology, or the vapor phase of oceanography

2. Above 1 meter	The surface film Model studies
3. Above 20 meters	The diurnal heating zone Harbor problems Coastal problems
4. Above 200 meters	The wind-stirred layer Continental shelf studies
5. Above 1500 meters	The main thermocline Slope studies
6. Between 4000 to 6000 meters	The depth of most of the ocean bottom
7. Between 6000 to 9000 meters	The oceanic depths
8. Below the bottom	The temperatures within the bottom

The range in time scales for various oceanographic processes is probably greater than the variation in depth ranges. Figure 3 illustrates in a logarithmic way time scales varying by 10^{17}. Occasional investigators have worked on problems near the top or bottom of Fig. 3 and these excursions may well have a great influence on oceanographic research; more are to be encouraged.

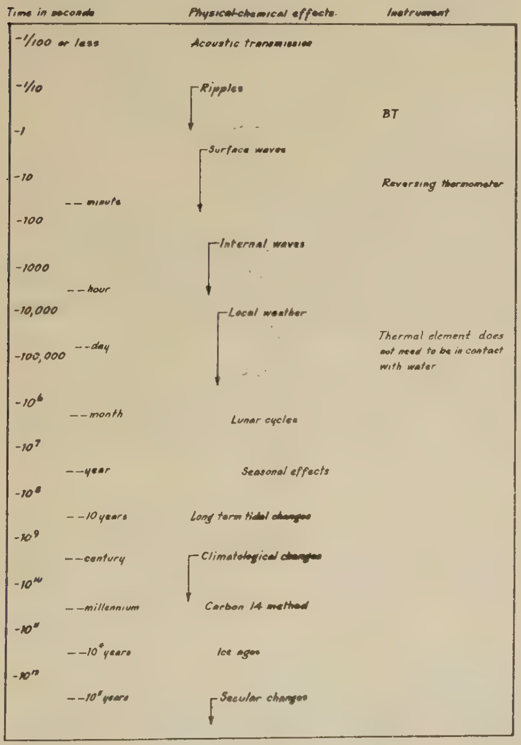

Fig. 3. Time Scale

To date the vast majority of the thermal work in oceanography has been done in the time range of from one day to one year. Even the periods associated with internal waves have received only a small amount of effort while on the other end of the scale the long range problems have only recently been receiving much attention.

It can be seen from Figs. 2 and 3 that certain depth ranges and time scales are relatively unexplored by virtue of the lack of adequate instrumentation. Recommendations of these instruments will be made in a later section.

POINT OR CONTINUOUS OBSERVATIONS

In order to properly study and interpret the ocean we would like to get continuous information regarding it. In other words we would like to know not only the temperature at a point but also the time and the three space derivatives of temperature. Now obtaining continuous information in both space and time would present impossible problems of both instrumentation and data handling. We need, therefore, to devise our experiments and instruments so that we obtain as many observations as practical in the most logical manner. It would seem that the criteria of how many observations are needed will depend upon our ability to interpolate between our observed points.

Investigators are apt to become over-confident of their work on the basis of observed points which fit a given assumption. This can be quite dangerous, particularly if the assumption was made after the data was taken. I would like to add a word of caution and recommend that the precision of a set of temperature-depth points be determined by "the reliability and precision of interpolated temperatures" rather than on the temperatures at the measured depths.

Because it is not mathematically feasible to determine the precision of interpolation along an unknown curve, we interpolate from point to point on the basis of an assumed temperature-depth distribution. For example our mind will usually only permit so many inflection points. In other words, our precision of interpolation is intimately connected with how many inflection points we think exist in the actual curve.

In order to arrive at thumb rules for interpolating data of this kind, I would suggest that in areas where the temperature structure is well known and appears linear, we can interpolate to within say 2% of the temperature difference between thermometers. Where the temperature structure is not well known, or is not nearly linear, it is doubtful if we can estimate temperatures to within 5% of the difference between temperatures. In essence, it is emphasized that important small scale fluctuations can exist in the temperature structure of the ocean and escape our present methods of measuring and analysis. I would, therefore, suggest that we tend to think of a temperature-depth trace as a fuzzy band rather than as a mathematical line. Furthermore, we should remember that this band is opaque, and much of the future progress in oceanography will come through learning more about the small scale changes.

Figure 4 shows a set of temperature-depth points with several types of interpretation made on the data to illustrate the points in question.

First, we have a smooth line drawn connecting the points as one would normally do. Second, we have a series of rectangles with opposite corners connecting adjacent points. While a total error as large as the area of these blocks is perhaps ridiculous, we must remember that any one point could make an excursion as great as this without even introducing a reversal of temperature.

Third, we have placed a pair of temperature points midway in depth between observed points assuming that we can interpolate to within about 5% of the temperature difference between points. Then we have drawn a wide line to indicate the extent of the fine structure which may still be beyond the powers of our data to disclose.

I want to emphasize that most of our deep water theories of the ocean have been built up on a mass of data which is incapable of showing fine structure, particularly as usually analyzed.

ERRORS IN TEMPERATURE DATA

In taking and interpreting any oceanographic temperature measurement we must remember that many factors come in. Components of error are numerous, and oftentimes very subtle. A listing of some of the sources may help

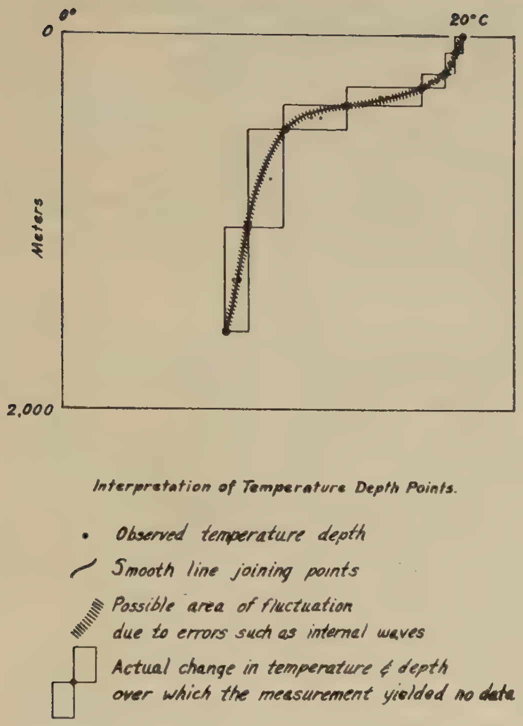

Fig. 4. Typical set of temperature-depth points showing range of possible interpretations.

clarify the problem somewhat.

a. The primary measuring element will have its own internal hysteresis and thermal time constant.
b. The recorder will have its own hysteresis and time constant.
c. The time or depth scale will have its own hysteresis and time constant. These time constants make a low pass filter of the recorder.
d. The phenomena we are measuring may well be changing both spatially and timewise, for example, in the presence of eddies or internal waves.
e. In all probability our measuring instrument is being dragged or is oscillating vertically and horizontally through the structure we are trying to measure.
f. If we are trying to measure small structures we are confronted with the finite size of the measuring probe.

The dynamic size of a thermal element can be many times the actual size and it must be known and understood for each piece of equipment. Instead of the actual size of the probe one should visualize a fictitious temperature element whose size is as large as the actual size plus the product of its thermal time constant times the speed the element is moving through the water. The time constant is the time required for the thermal element to come to within a given per cent of the final temperature. This is usually stated as the time to come to within 37% of the final temperature. In a thermal system the response is usually logarithmic and will have the following response:

Time	Approach to Final Temperature
θ	37%
2θ	13%
3θ	5%
4θ	2%
5θ	0.7%

A bathythermograph will have a time constant of about 2/10 seconds so if it is falling 10 feet per second its thermal element will be effectively 4 feet long if it is to respond within 13% of the temperature change and effectively 10 feet long if it is to respond to within 7/10% of the temperature change.

It is very difficult to make a rugged thermal element with a rapid speed of response although the state of the art is improving and some commercial manufacturers are making higher speed elements. Even an infra red device will not give true surface temperatures because it will respond to an average temperature of the top few tenths of a millimeter of water.

THERMAL SENSITIVE DEVICES

When making a thermometer one should think carefully of how temperature affects various substances and structures and select a primary sensitive element which:

a. gives a large output per degreeC. This usually should be measured in units of work per degree;
b. has good thermal stability over the period of time in question;
c. is not unduly affected by pressure;
d. is reliable;
e. has sufficient speed of response;
f. does not have different time constants for different parts of it;
g. is not too sensitive to vibration. Here one wants a short natural period.

The choice of thermal elements is fairly large and a particular application may dictate a particular choice.

1. Thermal expansion of a gas. This will permit large work outputs and is convenient except for its very large pressure coefficient.
2. Thermal expansion of a fluid. This is commonly used and can have good reliability and a large work output. Mercury thermometers and BT's are typical.
3. Thermal expansion of a solid. This has the least motion and most designs have either a slow speed of response or are sensitive to vibration. Bimetallic elements are used in the thermo sonde.
4. Change in the electrical resistance of a metal or conductor. Resistance thermometer bridges are stable, accurate and well understood. Thermistors are certainly coming into their own and while they still lack long time stability they make it possible to build a cheap and sensitive thermal element. Their high resistance makes them very good for inputs to servo amplifiers.
5. Peltier effect - the emf produced by a thermocouple. The power developed in a thermocouple circuit is very small but it is well adapted for comparing temperatures at several different points.
6. Vapor pressure thermometers are widely used in industry and they are based on the vapor pressure of a given fluid.

INSTRUMENT DESIGN

It is impractical to recommend a specific method without knowing the problem and the techniques available to the builder. Personnel preference, training and ability will usually determine how an instrument is built. The following notes may be of value to designers.

a. Mechanical levers. If the primary measuring element gives a large work output it may be practical to use mechanical levers for amplification. When well done this method is simple and reliable. Such systems are sometimes allergic to vibration. If bearings are used corrosion can be a number one problem.
b. Optical levers. These have the great advantage of giving high magnification and being almost inertialess. Another great advantage is that several traces can be lined up and still overlap.
c. Servo systems. The use of an electrically operated self-balancing bridge is perhaps the most versatile system as it can be operated with very small inputs and can give a large output. Many manufactors produce a wide variety of commercial servo systems.

d. Recording methods. There are several mediums available for recording data and the writer does not pretend to know them all. However several are listed to indicate the range.

1. Smoked glass has been used with great success on the bathythermograph. Its advantages are high resolution, low friction and ability to withstand exposure to sea water. Its disadvantages of small size and inconvenience of smoke are real but are often of minor importance.
2. Waxed paper is commercially available, will give high resolution and in some cases will withstand immersion in water. It is usually available in rolls and can be used for long records.
3. Pencil or ink on paper is very good if the record is large enough. A conventional pencil or ink record on a paper or plastic surface is convenient to work with. Ink suffers from spilling if treated rough or smudging if the pen remains at one place. Most ball point pens will not give satisfactory service at slow writing speeds. A pencil requires a remarkably heavy pressure to give a satisfactory trace.
4. A photographic record is nowhere near as inconvenient as most people make out. The advent of the Polaroid Land Camera can sometimes further alleviate the problem. Photographic recording has many competitors but is probably the most versatile of all methods which give a visual record.
5. Magnetic tape can be used for recording temperature data with a wide range of coding schemes.

TYPES OF INSTRUMENTS WHICH ARE IN THE DESIGN OR TESTNG STAGE BUT WHICH ARE NOT GENERALLY AVAILABLE

One of the difficulties in oceanography is that most instruments seem to be in the design stage and are not generally available. It would appear impractical to more than mention some of the work which is going on as the individual investigator is the only reliable source of information in the early stages of development.

a. Scripps has had considerable experience and luck with their "Thermitow" which was designed to be towed near the surface of the water and record on a commercial electrical recorder on deck.

b. Devik of Norway has used an infra red pick-up to measure horizontal differences in the surface temperature of lakes.

c. Woods Hole Oceanographic Institution has been working on several variations of a recording thermometer which will record for periods of from a week to a year.

d. Several laboratories have considered the problem of a thermometer to be on the bottom of the ocean.

e. Combined temperature and conductivity meters or salinity meters have been built by the Bristol Company, WHOI, Chesapeake Bay Laboratory and the Navy Electronics Laboratory.

TEMPERATURE RECORDERS WHICH ARE NEEDED

There will be no attempt to recommend which of these following thermometers is the most important, because individual preference would vary widely. It does, however, seem advisable to list a few important instruments which still have to be made and become available.

a. A Rapid Response BT For The Top Few Meters: When studying the near surface problems, it would seem advisable to keep the recorders aboard ship and have only the measuring elements in the water. The chief problems here are to obtain a rather high speed of thermal response and to keep the measuring element very small. The measuring elements would probably be used in gangs horizontally or vertically. It would seem that a speed of response of 1/10 second and a temperature sensitivity of .01°C are required. The 16 channel thermistor-recorder designed by NEL is fairly close to this but the time constants are too long to study very small scale turbulence.

b. An Instrument For Studying Micro Structure And The Isothermal Layer: This instrument should have similar characteristics to the above instrument except that it only needs one element and needs to go to depths of several hundred feet.

c. A Reliable BT To 1500 Meters To Study and Survey The Main Thermocline: This instrument should be continuously recording with a temperature precision of at least .03°C. It probably must be self-contained although an ability to record on deck via acoustic data transmission would be highly desirable. A resistance thermometer might well be the most satisfactory measuring element.

d. A Sensitive Recording BT To Study Temperature Structure Below The Thermocline: In order to determine the characteristic and origin of deep water, it is desirable to be able to find any discontinuities in the deep temperature structure.

e. Infra Red Instrument to Study Heat Flow Across The Surface: The possibility of using an infra red sensitive device to look for horizontal temperature gradients on the surface of the water is very interesting. Used either by aircraft, or from a ship's mast, such an instrument may be extremely useful to delineate current and eddy boundaries in a way which would be impossible by conventional means. In view of the large temperature differences found in the ocean, it would appear that many very interesting problems could be attacked with fairly simple equipment.

Devik has published some work on surface temperatures in Norwegian lakes measured by infra red pickups in recent years. While the state of the art of such devices is rather limited, it would seem that standard bolometer techniques would permit seeing temperature differentials of a degree or two.

f. A Long Period Temperature Recorder: Oceanography has not had the chance to study temperature records extending over a long period of time and hence we are uncertain about how rapidly major thermal changes take place. In particular we do not know how important large transients, such as eddies, influence the temperature. Klebba of Woods Hole has designed a recording thermometer which can record for a year but it has yet to be used over any extensive period at a critical location. In coastal areas it will probably be wiser to have the recorder operate over a shorter time. The sensitivities of such recorders should probably be from 0.1 to 0.01°C and the thermal stability must of course be excellent.

g. A Bottom Temperature Recorder: A bottom temperature recorder such as the one designed by Bullard and by Scripps should be made available so that problems in heat-flow out of the bottom can be studied.

h. Cheap BT For Harbor And Limnological Work: A cheap BT for harbor and limnological work should be made. This does not have to be used underway and the depth ranges need only be 100 feet. Here I would recommend a bellows type pressure element working against an extension spring. The thermometer should probably be bimetalic as it is cheap and almost foolproof and does not suffer from over-temperature. Recording should probably continue to be on a smoked glass slide although a waxed card might be satisfactory.

i. Instruments Which Give Density, Salinity Or A T-S Diagram: As long as we are interested in density and salinity there will always be a need for an instrument that records or indicates those values continuously. Although the basic components for such instruments have been used by many groups their assembly into a completed instrument has not been done very often and the resulting instruments were expensive and complicated. Much more needs to be done along these lines.

DISCUSSION: E.C. LaFond

With regard to Vine's statement of the temperature-measuring instruments needed I would like to emphasize the depth range required for measurements in the region of the Sofar sound channel. Since the axis varies in depth from around 150 meters to 1100 meters, the instrument should be capable of providing detailed temperature information down to 1200 or 1500 meters. Such information is important to the Navy Electronics Laboratory in the study of long-range transmission and sound intensities in the Sofar channel. The details from the surface to the axis are more important than those below the axis; the latter information can still be obtained by reversing thermometers. On long cruises in the Pacific, standard depths are not used at present for sampling water and temperature through the region of the sound-channel axis, instead, 50-meter intervals are used. If a new BT were developed to cover this depth range, it is believed that a temperature-salinity relation might be used in certain areas to obtain the sound velocity by measuring temperature alone.

Vine brought out the desirability of using an exponential depth scale to emphasize the surface layers. This has been discussed before, and there appear to be two ways of modifying a BT to give this changing scale in depth. One is to use tapered wire in making up the pressure coil, and the other is to make the diameter of the coil turns successively greater.

Vine also mentioned the processes in the sea in which we are interested. The needed information may be boiled down to actual temperatures or changes in temperature. More emphasis should be given instruments that measure changes in temperature with time, depth, and distance. An instrument which gives the difference, for example, between the temperature at the surface and at any depth does not require as great a range as the universal instrument which measures actual temperatures; it can thus achieve greater accuracy and is easier to use. For most purposes, this difference in temperature is sufficent.

The thermal sensing devices and recording methods will partly depend upon the specific problems at hand. For example, temperature instruments built and used at NEL for specific studies are a TPR -- temperature-profile-recorder, a 16-channel temperature recorder, and a CTD -- conductivity-temperature-depth indicator.

The TPR was required to measure accurately the heat capacity in lakes, since the BT was believed to get out of calibration occasionally, thus nullifying the study. The TPR is a portable unit consisting of a thermistor sensing element, 6-volt power supply, amplifier, and an Esterline Angus recorder. The recorder is geared to the drum containing an electrical cable to which the bead is fastened. When the bead is lowered in the water, the paper on the recorder is moved accordingly. Depth is measured by the length of wire paid out; therefore, the instrument is confined to shallow depths and wire angles of zero degrees in order to record depth properly. This instrument was used on the Lake Hefner water-loss investigation for fifteen months and then recalibrated with no apparent changes in calibration. A report on this instrument has appeared in Journal of Marine Research by Anderson (1951).

The 16-channel temperature recorder consists essentially of 16 TPR's feeding into a single temperature recorder. It requires 16 cables and 16 beads which can be spaced at any desired depth or horizontal distances up to 200 feet. The Brown recorder used has one indicator that automatically shifts from one channel to the next, printing an indication of the temperature for one bead after another. This instrument was required for the study of thermal-pockets and temperature variability in the Arctic and the central pacific.

The CTD was developed at NEL for the study of simultaneous temperature and salinity changes in regions of convergence and during advection processes in the Arctic. The temperature-sensing element in this instrument consisted of a group of ten 14B type thermistors. The response and accuracy of the temperature element was surprisingly good. However, the speed of the servo mechanism was a little slow; the speed has since been increased by the Oceanographic Department of the University of Wasington.

The problem of measuring temperatures in ice in the study of ice formation was also solved by thermistor beads mounted in plastic with leads extending through the ice to a junction box. A portable, heated power supply and galvanometer were taken to the site to make readings for temperature.

The list of recorders which are needed seems to have been adequately covered by Vine; however, there are a couple of points about uniformity and availability of instruments which should be emphasized. If various organizations could point out their needs for temperature-measuring equipment and agree on a few standard types, it would be possible to have these manufactured in quantity and even stock-piled for major operations. It may be possible to standardize on units of temperatures as well.

DISCUSSION: R.O. Reid

Surface layer - It might be well to expand upon the discussion of the surface layer as introduced by Vine. A knowledge of the fine structure in the layer of water immediately adjacent to the surface can be of great value in our understanding of boundary transfer processes. Existing instruments show essentially isothermal conditions in the water within mixed layers; however, knowledge of the detail near the surface is deficient. From physical considerations, if there is to be heat conducted to the surface to replenish that which is lost by back radiation and evaporation, one should expect to find a decrease in water temperature with approach to the surface. The development of micro-oceanographic gear would be of value in disclosing such gradients very near the surface, if they exist, and in procuring quantitative data on these gradients for use in surface heat budget studies. Such instruments would also be useful in ascertaining the pattern of surface or near surface temperatures which reflect perhaps the pattern of evaporative convection cells in the surface layer. Temperature inhomogeneities would be most pronounced at the surface where unstable conditions of density structure could exist in the presence of processes of cooling.

Thermal Response Factors - It has been stressed by Vine that short response time is essential in certain types of temperature measuring instruments in the sea. This is certainly true for any moving instrument, such as the BT, which is essentially a temperature change measuring device. However, instruments, such as the reversing thermometer, which have long response times are useful and essential if one wishes to eliminate the short term fluctuations of temperature. The aim of the hydrographic cast is to obtain representative distributions of temperature, and to subdue any erratic variations, of periods less than one-half minute. The roll of the ship, for instance, will cause temperature oscillations in the environment of the thermometer. Because of the slow response of the thermometer, however, these oscillations will be damped out.

Accuracy of Thermometric depths - The accuracy of the thermometric measurement of depth by means of the (U)-(P)* pair of thermometers is severely limited in the region of the thermocline by virture of the motion of the wire and/or internal waves. The presence of a temperature oscillation in the environment of the (U)-(P) pair, together with the fact that the structure of the (U) thermometer is such that its thermal response time is much smaller than that of the (P) thermometer, brings about errors in depths by virtue of the disparity of the thermal response components in the scale readings. This can partially be eliminated by using some sort of standardized pressure transmitting plug for the (U) thermometer which will bring its response time up to a value more nearly corresponding to that of the (P) thermometer.

Reliability of Reversing Thermometers - A system of classification of reversing thermometers derived from the history of the individual thermometers is useful in the processing of data. It has been found useful in the work of the Marine Life Research Program at the Scripps Institution of Oceanography, as well as in the Gulf Survey Program at Texas A. &M. to classify thermometers according to the percentages of failures (a record of which is made on the hydrographic data sheets). In addition, the statistics of the discrepancies in readings between two (P) thermometers placed on the same bottle is useful in assigning a reliability value to the thermometers.

DISCUSSION: Theodore R. Folsom**

The importance of new instruments to the advancement of science is often mentioned and theoretical and experimental problems involved during development are frequently stressed -- but it is seldom stressed that plain manufacturing difficulties frequently limit availability. It is true that sometimes a long wait is required before a valuable flash of design inspiration occurs -- but all difficulties do not then simply melt away. There follows a painful period of trial and test -- and a sometimes much more painful period when physical construction is carried out.

Many scientific instruments require craftsmanship of exceptional quality, a commodity not so abundant in recent years; but whether skilled or unskilled, present costs are extremely high. To minimize this ever-growing expense two expedients appear necessary; an increased investment must be made in production tools of the labor saving type, and a search and procurement organization must be set up so that maximum number of mass-produced components can be incorporated in the needed apparatus. Space for new machinery and for the search organization must be provided. The staff must increase and the shop facilities soon become so large that the institution is able to see that it has entered the manufacturing business.

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* - (U) - unprotected; (P) - protected.

** - Dr. Folsom's discussion of Allyn Vine's paper has suggested to the editors a broad and important area not covered at the 1952 symposium -- the actual manufacture of research instruments, which is certainly a very large part of the whole instrument problem. The editors, therefore, have asked Dr. Folsom to generalize his original discussion with this point in mind. It is the editor's opinion that another meeting profitably could be devoted entirely to this subject.

Most research institutions long ago invested in elementary machine tools -- most of them soon found it necessary to separate maintenance shop facilities from instrument shops. Then the instrument shops in turn had to be expanded and subdivided; welding, drafting, and electrical operations required separate rooms. The expansion of instrument making facilities has followed a remarkably similar pattern in all academic research organizations.

Institutional instrument rooms often are beautiful to behold and appear to be models of efficient productivity. But the visiting V.I.P. is seldom told that down in the basement much of the equipment is duplicated for student use -- that institutional shops have very limited work-capacity -- and that whenever emergencies arrive the overload must be absorbed by resort to strenuous and generally inefficient measures.

Manufacturing inside the research institution is limited by several factors. The nature of the instrument and consequently its design and fabrication is unpredictable; thus it is not feasible to acquire all of the highly-specialized labor-saving tools that might be found occasionally useful. And it is impossible to retain on the shop staff a large number of specialists. As a result the standard, general purpose tools must be relied upon and the quantity of output can never hope to rise above a primitive level.

If the manufacture of instruments made within the institution is a limited and inefficient procedure, why is it attempted? This question comes up repeatedly. The general answer is that instrument development has proved most rapid and successful when the designer can be in close contact with the craftsmen who do the actual building. Maintenance of such facilities is admittedly expensive -- but on the other hand costs are likely to be even greater when the designer and the craftsman do not understand each other's problems thoroughly. This luxury cannot be carried to extremes, and opinion varies widely as to where the dividing line between formal and informal shop practices must be placed.

The internal shop facilities can no longer be more than token facilities, but it must not be forgotten that they contribute a most practical means for setting up contact with the outside manufacturing world. Interpretation and consultation regarding the technical merits of manufacturing proposals from the outside are commonly expected of the shop staff. The art of graphic specification -- drafting -- generally falls under the control of shop authority. It must be called upon when serious negotiations with outside factories are undertaken.

Just when outside agencies should be called in for duplicating or speeding up production of a well-developed apparatus is the subject of much discussion. Instruments are multifarious and diverse beyond all enumeration. It is not always possible to set up hard and fast rules so that a state of complete development can be recognized, and what might be a pilot-sized device in one field may be a production apparatus in another. The requirements for producing a few deep-sea coring tools may not be equivalent to those for many special hypodermic needles.

In certain instances outside manufacturing concerns become interested in the commercial possibilities of the instrument. This is rare, but it does happen. At this point the apparatus becomes an "invention", and takes on a mysterious character perhaps not originally associated with it. It is well that all concerned learn the legal rudiments of this situation. Although the institution and individual are not frequently rewarded, it is not uncommon for industrial concerns to proceed very slowly here. This points out that internal manufacture brings an often forgotten benefit -- privacy. And a whole lot can be said about the entirely different need for privacy in shops these days. Military security is now an additional instrument problem.

There seems to be little question but that the nucleus of an instrument factory must exist in a healthy research institution, but much of its value depends upon continued and skillful liaison with other agencies. It must maintain contact with industrial facilities, the shops of other research institutions, and the technological facilities of the government. And somehow it must learn to tolerate the learners, the graduate students, the workers in life-science departments. And somehow it must justify itself always with the bookkeepers who see the bills.

Contribution No. 697

ACOUSTIC INSTRUMENTATION AS A TOOL IN OCEANOGRAPHY *

J. B. Hersey

INTRODUCTION

Acoustic waves travel readily in sea water whereas all electromagnetic waves are rapidly attenuated. Consequently, except for rather short range examination, as is now achieved in underwater photography and television the only means presently developed, or likely to be available, for perceiving objects or events at considerable distances underwater is by sound. The sound perceived may be the natural sound generated by the object or event, as a sound-making fish or a submarine landslide, or it may be an echo from the object under study. The techniques described above have to do with sensing the presence of objects in the water or with analyzing the characteristics of things or events by the sound generated or re-radiated by them. The physical properties and structure of the water itself can be studied by analyzing the alteration of the intensity and character of the sound received from a known source as the relative position between source and receiver is varied. In addition there are various laboratory techniques for studying the physical properties of sea water. In some instances these are capable of working at sea, thus providing the oceanographer with a potentially valuable tool. This area of the art of underwater sound is the least developed outside of the laboratory.

The Nature of Acoustic Data - Virtually all acoustic observations underwater are made with the aid of a transducer which transforms a part of the energy from the acoustic wave to electrical energy in a circuit which, in turn, feeds some sort of electronic device. This drives some sort of presentation device which may be any of several types of recorder, a momentary visual display on an oscilloscope, or earphones or loud speaker. In common with most problems of instrumentation, systems for recording or analyzing acoustical data have a more or less vaguely limited range of usefulness for various problems. For example, the directional discrimination of a hydrophone varies with the frequency to such a degree that it is totally satisfactory for a given prescribed job only over a rather limited part of the spectrum. On the other hand, the same hydrophone is appreciably directional over a much broader spectral range and may well be usable for certain other problems so long as this variation is tolerable. Again, it is usually not practical to build an amplifier that has a constant gain over the whole range of frequencies of interest. Certain departures from such a "flat" response may be acceptable and often are desirable for some problems but not for others. All types of recorders distort the electrical signal fed to them by the amplifier. The nature and degree of the distortion must be known in greater or less detail for proper interpretation of the results. The list of these properties of acoustical instruments could be extended considerably. However, it is reasonable to expect that for a given problem instruments can be designed to serve the needs of the problem within limits that can be known. In any event acoustical instruments in general have rather complicated performance characteristics, and must be understood to a considerable degree by anyone who assays to interpret results from them.

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* - Contribution No. 697 from the Woods Hole Oceanographic Institution.

Even where the design of an electronic system is adequate a continuing and vexing problem is assuring stable, reliable performance. This is well known to many more people than have any real understanding of electronics. As a result we are all properly suspicious of any information that has passed through a vacuum tube circuit. This sort of suspicion runs riot on occasion, and can be quite dangerous scientifically, causing the investigator to ignore significant data on the plea that it was "some sort of electronic difficulty". This is an understandable attitude, but nevertheless, it is usually the result of not understanding one's tools. However, if an electronic system has been properly designed and tested for a specific job and is maintained as is required by the nature of it, it can be quite free of spirits and spooks. As a final note of suspicion, it is usually well to include circuits in the system that can test its reliability in the field.

In what follows acoustical instruments will be discussed in groupings according to the general type of problem in which they are commonly used. I shall try to describe in a general way the state of the art in each area, indicating the sort of instruments that are readily available to oceanographic research. These general groupings are: passive listening, acoustic ranging, sound transmission studies and echo-sounding and echo-ranging. I have had little acquaintance with acoustic laboratory techniques as opposed to broader scale field observations. Consequently, I hope this interesting field will be discussed by the other physicists later.

PASSIVE LISTENING INSTRUMENTATION

This technique is employed whenever the primary object of study is either man-made or natural sound, rather than the transmission characteristics of the medium. Broadly speaking this is the study of ambient noise; that is to say, the sounds heard at any given location caused by human activity or other natural agents. It may be used to detect the presence of and even locate ships, noise-making animals, submarine landslides, distant storms, approaching rain squalls, and seismic activity within the Earth, thus providing a basic observational tool in these several parts of oceanographic science. The quantitative study of ambient noise intensities caused by breaking waves, rain on the water, and other sounds caused by meteorological effects provides data which may well contribute to the study of energy interchange between the atmosphere and the ocean.

Until now most of the effort in this technique has gone into naval problems such as the detection of enemy shipping. The ambient noise of the sea forms the noise background which limits naval detection just as the self noise limits an amplifier, and consequently some attention has been devoted to the spectrum of ambient noise in a variety of locations typical for naval operations. A by-product of this work during the last war was a study of the sound-making habits of a small number of noise-making fish, crustaceans and cetaceans in their natural habitat. These observations have provided a jumping off place for scientific work. We know the order of magnitude of noise caused by moderately high winds, and we have a good impression of how quiet the sea may be on a very calm day, but this knowledge is confined to the portion of the spectrum between 100 cps and 10 kc. We also know something about the characteristic sounds of some noise-making sea animals. Beyond this we know very little. This is the case largely because very few people are using this tool in oceanographic science. Passive listening gear is the simplest sort of acoustic system with which to observe. However, if it is to be used for any purpose save that of listening to and evaluating qualitatively the sounds of nature it may be demanding and complex. In the past ambient noise has been studied for the most part with non-directional hydrophones. This study has now reached the state where knowledge will be most readily advanced with directional systems. I shall discuss only the non-directional systems in the hope that the other acousticians will be prepared to describe the sort of directional properties that can be achieved and the complexity of instrumentation required for the various frequency ranges.

Observations are frequently taken from shore, but usually some sort of boat or ship is required to go where the problem is, or perhaps merely to get away from the excessive self noise of the shore. The first requirement on the boat or ship is that it be capable of sitting quietly in the water. No refrigerators, no galley range, no main generator can usually be tolerated in operation while observations are in progress. Electric power for the electronic gear is preferably obtained from storage batteries which power a small motor generator set which is very carefully shock mounted to isolate its vibrations from the ship. In short the ship is de-commissioned except for this single power system. When operating from small craft very light convertors or vibropack power supplies similar to those used for automobile radios have been used. A small rowboat has been used successfully to carry a complete amplifying and recording system powered by a 6 volt storage battery, B batteries and a vibropack.

For non-directional listening and also the simplest directional systems the principal instruments are the hydrophone, an amplifier, earphones and usually a recorder. There is available an array of essentially non-directional hydrophones sensitive to the audible range of humans. In this frequency range the workhorse of our group and many others is the Brush Development Company's AX58 series. A higher quality, but somewhat more fragile instrument is the Bell Telephone Laboratory's 5E. Both are World War II designs.* The AX58 types generate about one ten thousandth of a volt when in a plane sound wave whose pressure is 1 dyne/cm^2. The 5E has about one third this response. Their response to greater or lesser pressures is approximately linear over a considerable range. They are both usable with suitable modification of their pre-amplifiers from well below 10 cycles per second to about 10 kilocycles. Above this frequency their directional properties make them unsuitable for most quantitative work. At higher frequencies various hydrophones have been designed for non-directional reception. I am not thoroughly familiar with any of them, but understand that the Brush Development Company makes a useful instrument. One word of warning about high frequency hydrophones as a class is worth observing. Comparatively few of them are non-directional except in one plane, and the designer of the particular observation must bear this carefully in mind.

If adequately quite pre-amplifiers and amplifiers are used with either the AX 58 or the 5E the self noise of the listening system can be made somewhat quieter than the quietest ambient noise thus far observed at sea between 30 cps and 20 kc. So far as I am aware the same can be said for systems designed for use above 20 kc. However, the use of small assemblages of sensitive elements in the hydrophone to avoid directionality in this range makes for a less sensitive hydrophone, which, in turn, means a relatively higher self noise except where the impedance of the sensitive element can be kept low. High quality hydrophones operating at high frequencies with low self noise are normally designed to be resonant hydrophones operating in the neighborhood of resonance. At frequencies below 30 cps there is no considerable body of quantitative experience at sea. The principal problems in this region appear to be in the proper quiet handling of the hydrophone rather than electronic design.

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* - Several hydrophones are being produced by various companies. These are just beginning to be used by The Woods Hole Oceanographic Institution but at this writing we can give no evaluation of them for underwater acoustics as applied to oceanographic research.

Whenever directionality is desirable in the hydrophone system, which is frequently the case, single hydrophones having large directivity indices are available only in the region above about 10 kc. Of this type a well known example is the early World War II QBE, a directional transducer designed for an echo ranging system operating at 24 kc. It has all the disadvantages of a tuned system, but is not so sharply peaked that it is completely useless at other frequencies. For the low frequencies the designer is on his own and may construct any of a wide variety of hydrophone arrays to suit his particular requirements from the simple "figure 8" pattern of a two element array to the sharply directional multi-element arrays. There is no circuitry generally available with any considerable body of experience behind it for the use of arrays in the low frequency field. This lack is becoming a serious shortcoming as field observations and understanding of this part of acoustical research progress.

The choice of amplifier and recorder used in taking field data is determined by a number of factors, some of which are not the least bit obvious at the outset except to experienced investigators who have suffered from past failures. For example, shall a high quality recording of the sound be attempted for relatively short periods, or will it be more advantageous to obtain a recording of lower quality which can, nevertheless, be made continuously over long periods of time? Is it wise to use some photographic process for recording that requires the records to be developed a considerable time after the tests? High quality records may result but you are assured that you won't know your data until it's too late to change a faulty procedure or try a new idea. Shall rather complete reliance be placed on the "quick and dirty" answer to be obtained from visual observations on a sound level meter or perhaps some such crude recorder as the type which records sound intensity as relative blackness on a chemical recording paper? The list could be continued. The state of understanding in the particular problem and the object of the particular observations are usually supposed to be the principal determining factors. Actually acoustical research groups as well as individuals seem to have developed rather arbitrary preferences in recording and subsequent analysis. For such standards as there are, underwater acoustics is wholly dependent on such related fields as air acoustics and seismology.

In passive listening one is usually interested in the quality as well as the intensity of the sound, and earphones or loudspeakers are apt to be used for observations somewhat more than an output meter. Except for the crudest sort of tests it is desirable to make some sort of recording that can be played back at a later time for analysis. The usual hydrophones, such as those mentioned above, have so low an output for sounds ordinarily to be heard that some sort of pre-amplifier is required between the hydrophone and any commercial recorder. While it appears on the surface that a stage or two of amplification with perhaps a third stage of cathode follower for matching is all that is required for the job, it has been our experience that a sufficiently versatile pre-amplifier for more than a very restricted use ends up as a rather high gain amplifier incorporating within itself provision for covering a very wide dynamic range and a wide choice of filtering, as well as built-in conveniences for electrical calibration. Such an amplifier is not required to take high quality observations, but it is a great time-saver in a continuing and somewhat varied acoustical research program. We started the development of such an amplifier in 1947 and called it, somewhat hopefully, the SUITCASE. I shall describe it briefly as an example of a rather versatile amplifier for passive listening.

In the beginning it was intended to be sufficiently portable that one man can carry it as hand baggage. For various reasons the SUITCASE has become an instrument which occupies a 12 x 17 inch rack mounted chassis and requires at the least a rather heavy alternating current power pack to operate it. The other alternative is a heavy duty 6 volt storage battery plus seven heavy duty B batteries. It is no longer regarded as one man's hand baggage. This amplifier contains two channels which may be connected separately to two hydrophones or in parallel to a single hydrophone. Both channels have a flat response with a minimum of phase distortion between 10 cps and 30 kc. They are designed to be fed by a low impedance line usually coming from a cathode follower contained in the hydrophone. No transformers are used in the basic amplifier, thus avoiding the distortion caused by them. The wide dynamic range is provided by designing the basic amplifier so that it will give an undistorted output of 1 volt across 500 ohms for an open circuit voltage input on the hydrophone crystal of about 0.5×10^{-6} volts compared with an equivalent self noise of about 3.0×10^{-6} volts in a frequency band 20 kilocycles wide when used with an AX 58 hydrophone. It further provides two step attenuators, allowing between them 120 db of attenuation in two db steps. That is, sounds whose pressure ranges over a factor of a million can be made to pass with small distortion through the amplifier. The maximum dynamic range of the suitcase at any given setting of the attenuators is about 50 db when properly adjusted. Obviously such a dynamic range cannot be realized for all settings and must be investigated for each use. The important point in the design of this instrument is the placement of the attenuators with reference to the stages of amplification. These attenuators are so placed that with proper manipulation the only vacuum tube preceding them is the cathode follower in the hydrophone, which will take about 10 volts on its grid without distortion. Two interstage filter positions are provided in each channel. A vacuum tube voltmeter is built in with selector connections to the output of either channel as well as to the input of a calibration circuit designed to introduce an electrical calibration signal in series with the crystal of either hydrophone.

The 1 volt output is adequate for feeding any of the common commercial recorders of the disc or magnetic wire or tape variety. It is not adequate for driving the pen of any of the common direct writing recorders. For this use separate drivers have been designed which will feed pen recorders full wave signals within their frequency response range, or rectified and averaged signals for higher frequencies.

For recording ambient noise, animal sounds and complex sounds in general the magnetic tape recorders have proven to be the most satisfactory sea going instruments having adequately broad frequency response. This does not mean that disc recorders, magnetic wire recorders or any of the photographic recorders may not be used, but they have severe limitations in one direction or another. Disc recorders require very close attention and do not operate too satisfactorily on a rolling ship. Wire recorders have a restricted frequency response, and the photographic recorders, while excellent for many purposes require considerably more technical skill and attention than the tape recorders, thus reserving their use for special problems. This general class of recorder stores the data so that it may readily be played back, providing a more or less accurate electrical copy of the original sound pressure fluctuations. We now feel that this sort of record should be made of most underwater sound observations. However, other presentations are required for various types of analysis.

The analysis of a passive listening observation may consist of determining the power spectrum, if the sound is approximately random noise or a steady state sound. This may readily be done with a series of band pass filters feeding one meter in turn or, for multichannel operation, several meters simultaneously. However, the usual technique now employed is to play back the previously recorded observation through the appropriate filters to a meter. The design of the meter is somewhat arbitrary, and there are engineering standards which it is frequently desirable to follow so that the results are readily to be compared with others. The nature of the sound will determine the design of the filters required for its analysis. For many ambient noise studies rather broad band pass filters suffice, whereas for some problems it may prove worthwhile to employ exceedingly narrow band filters to reveal significant detail such as fine lines in the spectrum. In general each problem has its own filter requirements and the acoustician should be prepared to use a variety of filters in the exploratory phases of a problem.

If the sounds are transient in character, or if they vary in composition even rather slowly with time, it is highly desirable to conduct the frequency analysis so as to reveal these fluctuations. This art has been intensively used in geophysical exploration and has already been discussed by Dr. Raitt. There the usual technique has been to employ a multichannel amplifier with band pass filters so chosen as to reveal the significant details of the spectrum for the particular problem. Recording is commonly done with a multichannel oscillographic camera. In some instances sufficient information can be recorded with direct recorders using pen and ink or heat or spark techniques. After trying all three of these techniques we tend to prefer the heat recorders where photographic recording is not required, since the hot wire pens are less of a maintenance problem than the pen and ink. However, good results with spark recorders have been obtained recently.

The sound spectrograph developed at the Bell Telephone Laboratories and produced by the Kay Electric Company as the Sonagraph and Vibralyzer are somewhat in a class by themselves as analysis tools for revealing the detailed variations in the spectrum of a sound with time. While the importance of these instruments to underwater sound analysis merits a detailed description, the basic design is thoroughly described in the literature (Koenig, 1946). The commercial units are designed to cover in some detail the frequency region from 2.5 cps to 8800 cps in several steps. The length of the sound sampling analyzed in one recording varies inversely with the extent of the frequency range from 2.4 to 20 seconds. The available frequency range can readily be extended by playing the original record at multiples or sub-multiples of its normal recording speed. The time variation of the spectrum is presented as relative blackening on a spark recording paper. This qualitative presentation is supplemented by a function of the instrument which presents the spectrum quantitatively at any chosen time. It has not proven difficult to supplement the basic circuitry to provide a function which takes the average spectrum over a time interval whose length may be continuously varied over a considerable range.

In the year and a half we have been using these analyzers they have proven extremely useful in revealing frequency effects in shallow water transmission, bottom reflection phenomena and biological sounds. In passive listening the sound spectrogram appears to have the same sort of range of usefulness it has in the visible speech analyses of the Bell Telephone Laboratories, and for much the same reason; they provide an objective basis for comparing the quality of sounds. The spectrogram will be especially useful in identifying biological sounds. In most cases the animals are not identified and it is often difficult to reconcile the descriptions of these sounds made by different observers.

This technique should go a long way toward providing a satisfactory means for comparing observations taken at widely different places and times. Other examples of the use of these instruments are cited under other topics below.

ACOUSTIC RANGING TECHNIQUES

Distances in open water can be measured by acoustic ranging with considerably greater precision than is possible with any other technique. The instrumentation required is exceedingly simple. A sharp transient sound such as an explosion is initiated at one of two points whose separation is to be measured and a listening hydrophone is placed at the other point. The instant of detonation of the explosion, if that is the sound source employed, is either transmitted by radio to the receiving point, or compared very accurately with a break circuit navigation chronometer or with a radio time signal such as from WWV. In this latter case the arrival of the sound at the hydrophone is compared with a similar break circuit chronometer or radio signal at the listening point. If the initial sound is received by radio at the receiving station the acoustic travel time is easily read from a single record at the receiver. If radio time comparison is employed the start of the sound and its arrival can be directly compared simply by comparing the two records. If break circuit chronometers are used than the necessary procedure is to compare both of the chronometers with such a common time base as WWV or carefully compare the chronometers themselves as often as is indicated during the survey. The technique of transmitting the shot instant by radio works well with radio equipment ordinarily available for scientific work at sea only to rather short ranges, say to the order of 50 to 75 miles. At greater ranges it is usually necessary to employ the comparison method. In any case the data provided is the travel time between the two points for some acoustic transmission path. The computation of range from this travel time is exceedingly simple in some instances, i.e., when it is known that the first sound to arrive follows a relatively simple, direct path from the source to the receiver. The distance is obtained simply by multiplying the speed of sound in water by the elapsed time between the start of the sound and its arrival at the hydrophone. In many other cases the situation is considerably complicated by there being many paths over which sound energy will travel and be readily distinguishable by the receiver. Hence it is very important to know the nature of the paths and the sound intensity associated with them as well as their relationship to the direct line distance between the two points. Another complication of the problem may be that low frequency energy will arrive at the hydrophone before higher frequency energy. This means of course that it travelled by a different, more rapid path between the two points. In order to measure range adequately in such a situation it is first of all necessary to understand the transmission properties of the location and, second, to make proper use of filters in the electronic receiving equipment at the receiver in order properly to interpret the acoustic records in terms of distance. It seems quite unnecessary to go into details of the instrumentation required for this sort of use of underwater sound. The receiving hydrophones and amplifiers and indeed the analysis equipment, when any complicated analysis is required, are exactly similar to those described under passive listening techniques. It might be worthwhile to point out that crude ranging gear can be utilized for certain problems where the underwater sound transmission properties are not unduly complicated and the precision of the distance measurement does not have to be very great. The simplest sort of receiver with earphones or a loud speaker and a comparing watch synchronized with a similar timepiece at the sending point may be quite sufficient for obtaining distances precise to within a mile over distances up to easily 20 or 30 miles, and considerably greater under the right circumstances.

SOUND TRANSMISSION STUDIES

It is evident from the preceding discussion of sound ranging that for the use of acoustics as a survey tool, it is essential to understand the details of sound transmission in the area to be surveyed. Sound transmission studies are also valuable as a means of understanding the physical properties and structure of the sea water itself and of its principal boundaries, the surface and the ocean floor. The subject is involved and has been pursued on a number of levels of complication for various purposes. For instrumentation, attention must be paid to the receiving equipment and the sound source; and for the experimental procedure one must consider the location of both source and receiver in both horizontal separation and depth. Again the instrumentation described under passive listening serves as the receiving equipment in all instances. The particular facet of the transmission problem to be studied determines to a large extent the type of source employed. A great deal of use has been made of underwater explosions as sound sources for studying transmission properties and they are the workhorse of several experienced groups in this field. They have the advantage that the initial sound consists of a very short transient whose pressure-time curve is approximately an exponential and whose spectrum, though far from white, nevertheless contains a considerable amount of energy over a very wide frequency range. Hence TNT is a very important instrument in underwater acoustics. Explosives research during the war, particularly at the Underwater Explosives Research Laboratory at Woods Hole has made a considerable contribution to the art of underwater acoustics by supplying a great deal of detailed information about the properties of shock waves in water. Much of this information is available in the book entitled "Underwater Explosions" by Robert Cole (1948).

In addition to explosives, transducers which are similar to the hydrophones we have already been discussing can be powered by an electronic oscillator and driver to produce intense sound at a single frequency. These are very useful for studying the effect of the environment on transmission in a restricted frequency range. Whenever the needs of the problem at hand are either adequately or best served by single frequency transmissions there are an excellent array of transducers available to cover a wide range of frequencies. However, I feel that the use of single frequencies in a scientific research program on sound transmission is not nearly as fruitful as the use of a source having a complex spectrum. This is because the present need in this field is for an understanding of the relative importance of different environmental factors as a function of frequency and for knowledge of how their effect may vary geographically and seasonally. For this work, explosives or other sound sources having a complex spectrum with appreciable energy distributed over a wide frequency range are direct and economical tools for the job. There is no single complex sound source which is completely satisfactory over this whole range for one reason or another, with the possible exception of explosives. There are various devices such as underwater sirens, electrical sparks discharged under water, certain fuels which can be burned under water and various mechanical devices which expend energy acoustically by a hammer driven by an electric motor beating on a steel diaphragm. All of these devices are moderately intense sound sources and can be used for sound transmission studies. At present there is little published information about complex sound sources. A discussion of some of them in Beranek's "Acoustical Measurements" (Chapter 9) indicates their general properties.

It is important to note in connection with sound transmission studies, particularly where they involve complex sound, that the complete transmission system includes the receiving electronics, the amplifier, the recorder and also any analysis equipment that is used after the recorder. It is very important to understand the response of the whole system to the complex sound at very short distances in order to understand completely the effect of the medium in altering the sound both in intensity and in character. A second equally important problem of the same nature is to know the radiation characteristics of the sound source. Is it non-directional at all frequencies? If not, what are its directional properties? How stable is it? Does it give out sound of the same composition independently of time or of wear on the mechanical parts? Is it subject to breakdowns for which it should be monitored? The facts about explosive sound sources are interesting here.

The selection of the explosive is determined by available supply to a large extent but where possible pentolite should be used for smaller charges, say, of the order of a pound. This is because pentolite requires no booster and hence tends to be more reproducible. For larger charges, boostered TNT is entirely satisfactory. In fact the reproducibility requirements for acoustics are satisfied in most work by boostered TNT, even for small charges, since the lack of reproducibility is of the order of 2 to 5 per cent.

The shape of the charge is not especially critical where spherical waves are desired. Squat cylinders or spherical charges are accurately non-directional, but even such cylindrical shapes as a Mk 4 demolotion block ($\frac{1}{2}$ pound) or a conventional depth charge (300 pounds) are less directional than most so-called non-directional acoustic transducers.

Although the initial shock wave within a range of about 5 miles has a simple, wide Fourier spectrum it is followed by bubble pulses with a Fourier spectrum not expressible in simple analytical form.

The use of such complex sounds introduce transmission complications which must be considered in designing the experiment: the presence of reflecting surfaces causes reflections which make the actual Fourier spectrum at the point of observation vary as a function of range, charge depth and receiver depth, and in the case of echo experiments with the position of the echo target as well; also transmission characteristics vary as a function of frequency, and where these variations are not the object of study due account must be taken of them.

Mechanical sources are subject to wear and tear, but the few I am somewhat familiar with seem to fail acoustically, suddenly and in a manner that can be discerned by an experienced, alert observer. Electronically powered transducers can frequently be monitored acoustically. If this is not feasible, electrical monitoring of the power to the transducer is the best substitute.

ECHO SOUNDING AND ECHO RANGING

Both echo sounding and echo ranging employ instrumentation of a specialized sort to send out a sound signal which travels through the water to be reflected from the object under study and returned to a receiver. In echo sounding the usual object of study is the shape and depth of the bottom of the ocean. The echo sounder is also used for studying the vertical distribution of marine animals through a study of the Deep Scattering Layer. We now know that the Deep Scattering Layer is far more complicated than is implied by its simple sounding title. This layer may consist of one or several concentrations of sound scatters at various depths. The indication on an ordinary echo sounder of the scattering layer appears as reverberation, and the techniques for observing and analyzing the scattering layer records are somewhat similar to those developed for studying reverberation. As is well known by now, echo ranging was developed for the purpose of locating enemy submarines in wartime. Practical peacetime use of echo ranging has been proposed as a device for locating schools of fish, submerged wrecks that may be a hazard to navigation and as a direct aid to navigation in restricted waters. So far as I am aware, none of these functions has ever been employed in a concentrated, highly developed manner by anyone. The potential of echo ranging as a general research tool in marine biology and later as a practical device for locating fish is perhaps one of the most exciting possibilities for the use of underwater sound today. Several groups in this country and abroad are at work on the problem. Many ideas for instrumentation are undoubtedly being carried out and this particular subject deserves far more detailed attention for the purposes of this symposium than I am now prepared to give it. The typical echo sounder or echo ranger employs a rather high single frequency sound signal which may be radiated from the same transducer which is later to act as the receiver, or the radiator may be an independent transducer, separated a relatively short distance from the receiving transducer. Frequencies commonly used in this equipment range from 10 to 50 kc* depending on the use to which it is put.

The versatility of echo ranging or sounding instruments is such that it is possible with complete confidence to think of research in which echo information, namely the bearing, the distance to the object under study and the character of the returned echo, may be analyzed over very wide limits with appropriate design. For example, echo ranging techniques employing a separate sound source and receiver have been used successfully to measure the back scattered sound from objects as small as a single large prawn at a range of about one meter. On the other extreme, it has been a matter of routine to record reverberation from the scattering layers in open ocean at travel times corresponding to depths of 500 to 1000 fms. below the research vessel. The principal difference between the sort of information achievable in the one case and in the other is that individuals can be distinguished at very short ranges since there the directionality of both the source and the receiver is sufficient whereas at considerably longer ranges the same directional properties cause the sound to be spread out through a considerably larger volume so that back scattering is received simultaneously from many individuals. These directional properties are practical limitations in the gear readily available at the present time.

Commercial echo sounders are available in this country principally from the Raytheon, Bendix, Bludworth Marine, Edo and Minneapolis-Honeywell Companies. Most of the models have built in spark recorders and offer a choice of ranges from about 160 feet to 600 fathoms. They are built for fishermen, yachts and steamers; not for science. Echo sounders of greater depth capabilities are not generally available in this country, but have been designed for naval use or for special surveys such as those carried out by the Coast and Geodetic Survey. While these contribute steadily to our knowledge of deep oceanic bathymetry they are still a far cry from the instrument needed to supply many needs in oceanographic science. For example, all echo sounders are designed to have a total beam width of the order of 30° so as always to point in the general direction of the bottom when mounted on the keel of a rolling ship. As a result such a device becomes a very blunt instrument for delineating the shape of the ocean floor in any but rather shallow depths. Further, in order to keep the required transducer small for even such modest directionality, frequencies well above 10 kc must be used. These frequencies penetrate but a short distance into oceanic sediments and hence are only occasionally useful for mapping the thickness of the sedimentary carpet. Greater resolution of bottom shapes could be achieved by an increase of effective directionality. This in turn would have to be accompanied by a high degree of stability in the orientation of the transducer. This could be achieved quite practically by going to a larger transducer below the ship, not only for increased stability, but also to get it closer to the bottom. Penetration of the bottom can be achieved by employing lower frequencies. It is not impossible to incorporate all these features in a single device. However, it would certainly not be of any present commercial or naval interest, except for the data about the oceans it would produce. It appears to me that its development will have to come from scientific interest and out of research funds, and is a possibility in oceanographic instrumentation which merits serious consideration.

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* - Since this paper was originally presented the Minneapolis-Honeywell Company has introduced a commercial combination echo ranging and echo sounding device which operates at a considerably higher frequency.

The general theory of scattering from small objects has long demanded that marine scattering be studied with an acoustical system in which the scattering as a function of frequency can be studied in detail. A beginning has been made using an explosive sound source and a broad band directional receiver. Past instrumentation has been exceedingly crude acoustically, and is being developed as research in this field progresses. For analysis, similar techniques have been employed as in passive listening, and here the spectrograph type analyzers have proven very useful. This whole field requires extensive exploration and concomitant development of technique before its full potentialities will be approached. Its use as a research tool in marine biology or a commercial tool for fishing is just beginning. It is an exciting and promising field.

CONCLUSIONS

In the foregoing I have barely scratched the surface of problems which may be attacked in oceanography with acoustical tools, and I feel that the subject of available acoustical instrumentation has been covered only very sketchily.

Only beginnings have been made in the development of acoustics in oceanographic science. We have relied rather heavily on makeshift acoustical and electronic instrumentation. This picture is gradually changing, but it requires continued emphasis and the interest of competent acousticians and electronics engineers. At present very few thoroughly trained and experienced people are at work in this field -- I should guess less than two dozen acousticians and engineers who are relatively free to contribute to purely scientific research. With this sort of a roster progress can be expected to take place very slowly.

DISCUSSION: R. J. Christensen

Dr. Hersey has treated comprehensively the philosophy and general technical aspects of acoustic instrumentation. It is my purpose to comment briefly on several specific acoustic tools of limited application to the study of oceanography.

The first is the system devised for air-sea rescue, SOFAR (Sound Fixing And Ranging). This system employs a network of three or more hydrophones installed at an ocean depth near that of minimum acoustic velocity. Ashore monitoring stations, cable-connected to the hydrophones, record the signals received from explosive sources at distances up to several thousand miles.

Dr. Press has already pointed out the usefulness of these SOFAR stations in recording the "T" phase of signals of seismic origin, and Dr. Worzel has discussed the use of reflections of the SOFAR type of signal, in locating sea mounts and other types of lithosphere intrusions into the SOFAR sound channel.

Can the SOFAR installations be readily used to investigate water masses and similar large-scale phenomena also? In part, the answer lies in the ability of the investigator to disentangle the many effects which are integrated into the signal as it proceeds along its transmission path.

Received signals possess fair clues about the total length of path traversed and the direction also may be roughly inferred. However, no profound changes have been observed to occur when the length of the path is increased only by an amount sufficient to place the origin of the explosion from one side of a water mass boundary to the other. In other words, the intermass region between two large and distinct oceanic masses does not leave a large imprint in the signal when the transmission path in the intermass region is relatively short.

Since a high percentage of the transmission time for a SOFAR signal is spent in traversing the part of the ocean below the depth of minimum acoustic velocity, the use of SOFAR for the study of near-surface currents does not appear promising.

The installed SOFAR stations will be useful in studying oceanographic changes only after some reliable correlation is established between just detectible signal variations and measured changes in the physical state of the transmission path. No adequate means is yet available for describing simply the physical state of the path, especially where it traverses several thousand miles.

Echo-ranging equipment with high resolution in the time coordinate is the second acoustic tool to which I invite attention. Occasionally, the equipment presents scattering information from which unusual physical conditions may be inferred. Figure 1, shown through the courtesy of Mr. L. R. Padberg of U.S. Navy Electronics Laboratory, is a reproduction of a scattering record of the type recognized as different from the usual. The abscissa represents time after the emission of a short pulse signal, or the equivalent range from the echo-ranging ship to the scatterers. The ordinate represents the distance the ship moves along its course while taking the scattering observation. The blackness of the trace is indicative of the strength of the signal, the blacker the tracer the higher the strength.

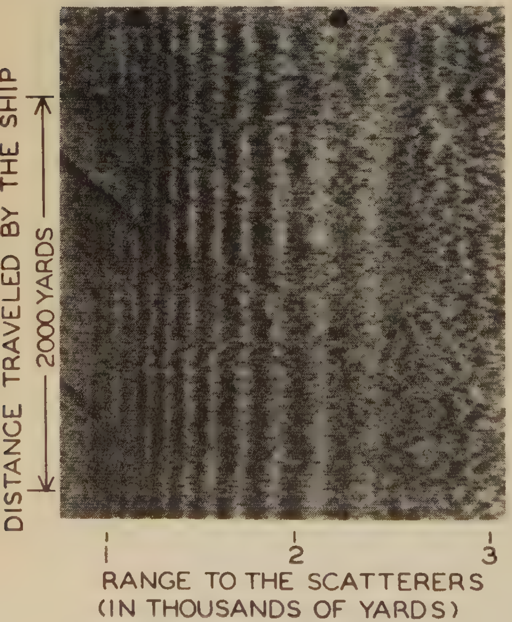

Fig. 1. Chemical recorder trace showing interference patterns resulting from scattering layer.

The light bands which are arranged in striking manner at particular ranges may be explained as a destructive interference in which some of the energy returned by the scatterers arrives via a direct water path and the rest by a path which includes one surface reflection. On the basis of this assumption and from the known geometry and equipment parameters, it is deduced that: the scatters are contained in a plane layer parallel to the ocean surface, the mean depth of the layer is about 300 yards, and the thickness of the layer is probably less than 5 yards. The depth of the ocean at the location was 400 fathoms and reflections from it are ruled out by additional evidence.

This particular phenomenon is found only occasionally. Even at the location of the above observations, it was quite localized. Equipment failure precluded delineation of its boundaries; but it was observed for a distance of 7000 yards along the ship's course, and it was not found at other positions nearby. Some areas display the phenomenon; others do not, apparently. On rare occasions, the interference pattern has been almost circular in shape, indicating a severe distortion of the layer from a plane configuration.

Significant to the purposes of this Symposium is the fact that here is a tool which infers some physical properties of the sea, responsible for the configurations of scatterers which do not appear to be completely explained by biological mechanisms alone.

The measurement of small current velocities existent in the ocean, would appear to be most reliably accomplished by a method utilizing "observation at a distance". Such observation could be made with a high frequency echo-ranging set which senses current velocity as a shift in frequency of sound returned by scatterers within the current. Tests have shown the feasibility of principle, but the packaging and the recording portrayal of the information for general application as an oceanographic instrument will require considerable engineering. Such a device, with little increase in complexity of the basic electronic assembly, could be constructed to give the three coordinate components of the velocity. It appears that measurement of current velocity as low as 0.1 knot would be entirely feasible.

The cross-correlator, a device applicable for precise determination of the time difference of arrival of two signals derived from a broadband frequency source, can be used in the study of underwater acoustic propagation to determine likely transmission paths. The method is most applicable to the case in which there are just several preferred paths. For a continuum of path lengths in which all paths share the energy more or less equally, the method would be of no value except to indicate the existence of such a condition.

Study of the acoustic properties of the ocean bottom, located near the water-bottom interface, can be aided by the use of techniques and devices developed for logging oil wells. Such properties as acoustic velocity, density, and porosity might be so investigated.

DISCUSSION: H.E. Nash

While the oceanographer and the underwater sound research worker have common interests in both underwater sound and in the ocean, they face these common problems from somewhat different points of view. The oceanographer is interested in underwater sound primarily as a tool which may be utilized to gain greater insight and more detailed knowledge of the ocean, including its boundaries and the life within it. The underwater sound researcher is interested primarily in the manner in which the ocean, its structure, its boundaries, and the life within it affect his ability to transmit and receive intelligence by means of underwater sound.

The general groupings chosen by Dr. Hersey for the framework of his presentation, i.e.: passive listening, acoustic ranging, sound transmission studies and echo ranging and echo sounding, when coupled with applicable laboratory techniques for measurement of the physical properties of the ocean define rather completely the areas of common interest. Like Dr. Hersey I shall confine my remarks to instrumentation for field observations.

One problem in which we have a common interest is the ambient noise of the ocean: its directional properties, its spectrum, and its relation to measurable properties such as wind force or wave height. Since animal sounds are sometimes a predominant factor in the noise background, it is important to know what animals are responsible for what sounds, as well as the seasonal and geographic distributions of these noise sources. I agree wholeheartedly with Dr. Hersey's feelings concerning the value of making magnetic tape recordings during the conduct of passive listening experiments. The possibility of obtaining an objective classification of animal sounds through the use of sound spectrograph techniques is extremely interesting and if successful will remove much speculation from this field.

Dr. Hersey noted that past measurements of ambient noise for the most part have been made with non-directional hydrophones and that the state of knowledge in this field can now be most readily advanced by the use of directional systems. This problem has been examined from a theoretical standpoint by R. J. Urick (1951) under the assumption that deep-water noise is of surface origin and that the radiation from an element of surface area is distributed in angle according to some power, $\underline{n}$, of the cosine of the angle with the vertical. Determination of $\underline{n}$, and its dependence on frequency and environmental factors is of considerable interest.

At the Underwater Sound Laboratory we have undertaken to build an electrically steered array to study this problem. The array consisting of thirty-six (36) individual hydrophone elements is shown in Figure 1. The element spacing is slightly less than one-half wavelength at a frequency of 8,000 cps, giving a total length of about ten (10) feet. Each element of the hydrophone is brought through its own pair of leads to a pre-amplifier and compensator which permits the array to be steered electrically from end-fire toward the surface, through the horizontal to end-fire toward the bottom. Compensation or steering of the array is accomplished through the insertion of time delay networks between the adjacent elements of the array so that only signals from a particular direction will add in phase. When no time delay is inserted, the array has its maximum response for signals (or noises) originating in a plane perpendicular to the axis of the line of elements. When a time delay is inserted, equivalent to that required for the acoustic wave to travel in the water a distance equal to the element spacing, the array will have its maximum response along the line of the array. For time delays smaller than this, the line of maximum response generates a cone about the axis of the line array and makes an angle θ with that axis,

where $\cos\theta = \dfrac{\tau c}{d}$

c = velocity of sound in water
d = element spacing
τ = time delay

The method of continuous compensation or steering employed with this array has been described by Holt (1947) and will not be repeated here.

At the half wavelength frequency this array has a directivity index which is independent of the angle to which it is steered. At frequencies lower than that required for half wavelength spacing, the directivity index in the "end-fire" compensated position is approximately 3 db higher than it is for the "broadside" position.

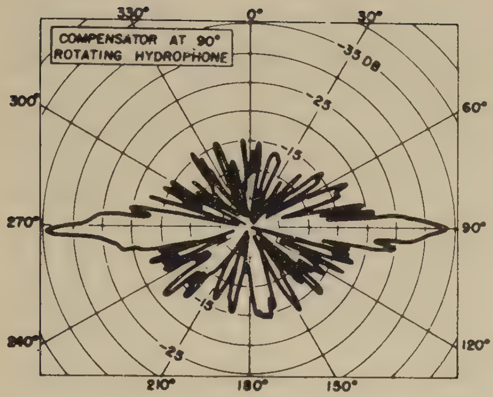

Fig. 2A. 10-foot Line Hydrophone with Compensator at 8 kc.

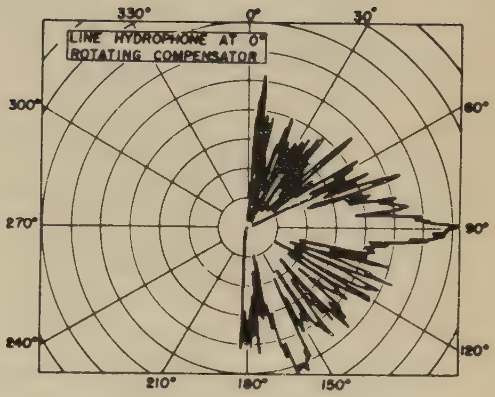

Fig. 2B. 10-foot Line Hydrophone with Compensator at 8 kc.

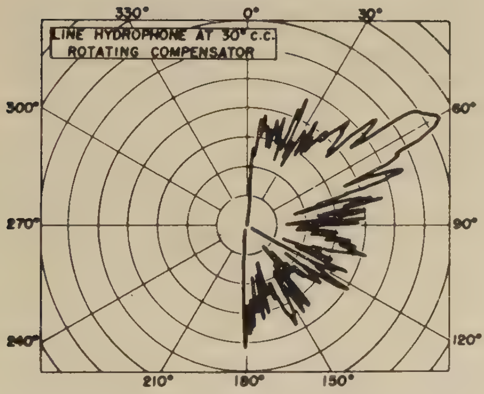

Fig. 2C. 10-foot Line Hydrophone with Compensator at 8 kc.

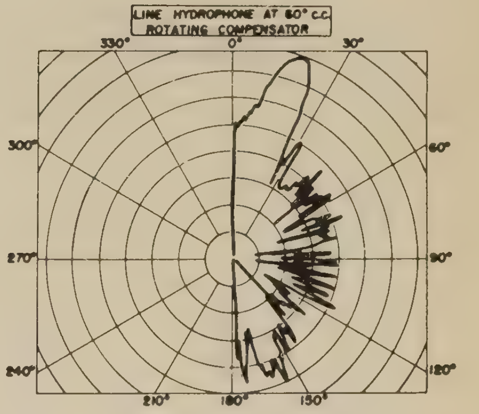

Fig. 2D. 10-foot Line Hydrophone with Compensator at 8 kc.

Directivity patterns for this array are shown in figures 2 and 3. The pattern of figure 2a was taken, with the compensator set at 90° (no delay), by rotating the line array about an axis passing through the center of the array and perpendicular to the line of the array. Figure 2b was obtained by holding the line array fixed and perpendicular to the direction of the signal source. Figures 2c and 2d are compensator patterns taken with the line of the array making an angle of 30° and 60° respectively with the direction of the signal source. The patterns of figure 2 were taken at 8 kc with the source approximately 60 feet from the array.

The patterns of figure 3 were taken at 2.5 kc. For each of these patterns, the compensator was set at a particular angle and the pattern obtained by

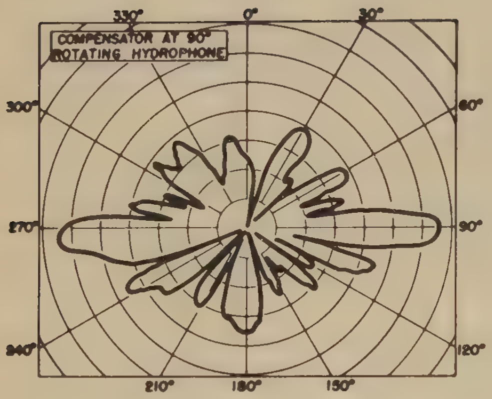

Fig. 3A. 10-foot Line Hydrophone with Compensator at 2.5 kc.

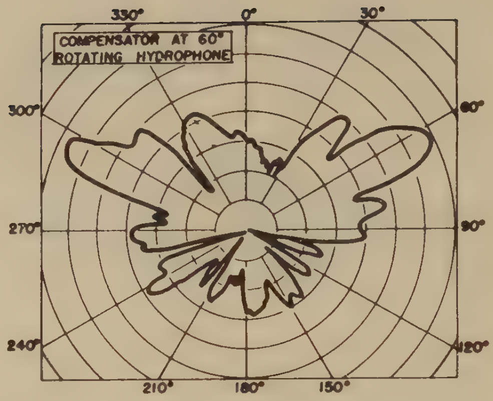

Fig. 3B. 10-foot Line Hydrophone with Compensator at 2.5 kc.

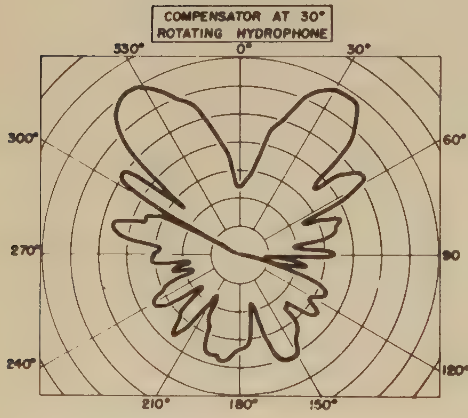

Fig. 3C. 10-foot Line Hydrophone with Compensator at 2.5 kc.

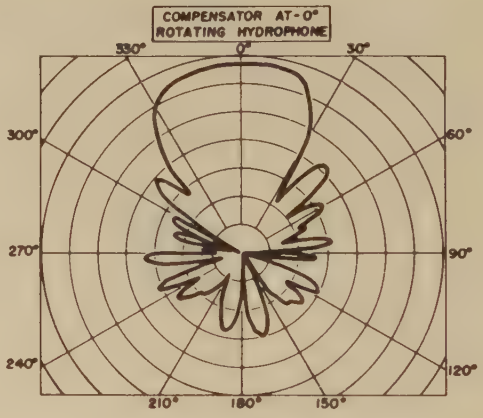

Fig. 3D. 10-foot Line Hydrophone with Comepnsator at 2.5 kc.

rotating the array. Because of the physical symmetry, the full three-dimensional patterns are obtained by rotation of the plane pattern about the 0^{o} - 180^{o} axis.

In application the line array is suspended and weighed so that it hangs vertically in the water. Directional patterns are then plotted by means of a polar recorder synchronized with the rotation of the compensator.

Figures 4a and 4b are compensator patterns taken in the field. In figure 4a the sound source is a projector and single frequency generator, while in fig-

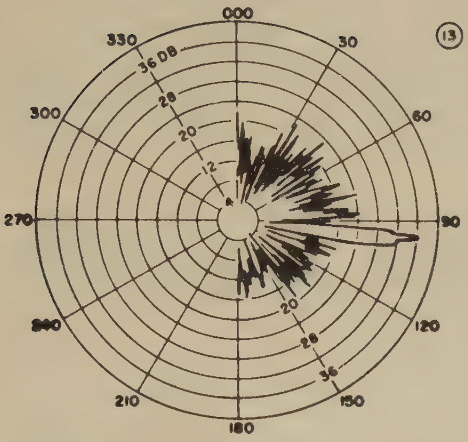

Fig. 4A. Signal from 20-foot Projector Hydrophone at 100 feet Range 12,450 yards.

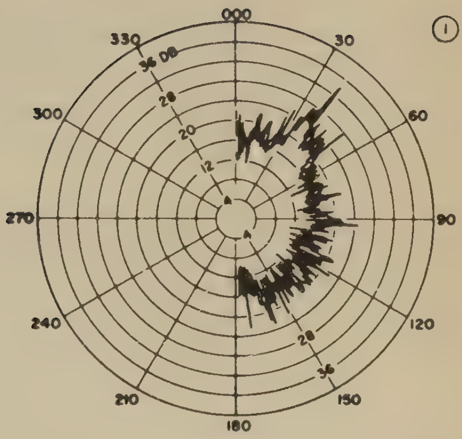

Fig. 4B. Noise-field Hydrohpne at 100 feet Receiver Attenuator at 0 db

ure 4b the directional character of the noise field 100 feet below the measuring ship is depicted. In figure 4b it can be seen that the major noise appears to be coming from a bearing of about 35^{o} with the vertical. This corresponds roughly with the location of machinery spaces on the ship from which the measurement was taken.

When utilized from a suitable platform, it is felt that the instrument described will permit an examination of the directional characteristics of noise fields over the frequency range of 1 to 8 kc. Refinements of the instrument should incorporate side lobe suppression even at the expense of somewhat broader directivity patterns.

A somewhat simpler system useful for a study of directional distribution

USS REHOBOTH

USS SAN PABLO

WIND FORCE	1	2	3	4	5	6	7
1	8						
2	9	5					
3	12	9	25	2			
4		15	23	92	23	1	
5		1	5	23	18	7	
6				1	10	16	
7					2	8	

Fig. 5A. Simultaneous Wind Force Observations (Beaufort Scale -- Cruise NINE)

USS REHOBOTH

USS SAN PABLO

WIND FORCE	1	2	3	4	5	6	7
1							
2	2	11	14				
3	2	6	37	12			
4		1	37	63	8	2	
5		1	9	27	29	47	1
6				2	11	19	2
7						7	4

Fig. 5B. Simultaneous Wind Force Observations (Beaufort Scale -- Cruise TEN).

of ambient noise at the lower audio frequencies has been suggested by C. J. Loda of the Underwater Sound Laboratory. This system consists of three pairs of equally spaced hydrophones placed along three mutually perpendicular axes (with proper isolation this can be done with four hydrophones rather than six). Each pair is connected in phase opposition so that three mutually perpendicular figure eight patterns are formed. By simultaneous comparison of the signals from the three pairs of hydrophones, information relative to directional distribution within the noise field may be obtained.

The spacing of the hydrophones in each pair is limited to that represented by one-half wavelength at the highest frequency to be used. The lowest usable frequency will be determined by the sensitivity of the hydrophone pair and the receiver noise. Amplification before combination of hydrophone pairs will be necessary if this scheme is to be used when the spacing is very small compared to a half wavelength at the frequency in question.

The Underwater Sound Laboratory has been engaged for a number of years in the collection of underwater sound propagation data, including measurements of reverberation and ambient noise. In order to handle expeditiously the large volume of data being accumulated, it was decided to establish a small IBM calculating unit. While this hardly falls in the realm of underwater sound instrumentation for oceanographic research, the IBM equipment is a tool which has permitted the study of problems which we would not otherwise have considered. In addition to providing a versatile facility for rapid analysis, the IBM installation insures the orderly storage of basic data in a form useful to future investigators.

Having once established such a computing facility, we have found it desirable to give attention to the manner in which data are collected so that they may be most efficiently processed by the machines. Where meter readings are made in the field, the data are recorded on mark sensed IBM cards so that upon return to the Laboratory the machines can immediately be put to work. However, for many applications, photographic film, paper recording tape, or magnetic tape are the most desirable medium for data collection. It was, therefore, necessary to provide for rapid reading and transcription of such records. For this purpose the Underwater Sound Laboratory utilizes a Telereader* and Telecorder.

The Telereader is capable of handling either translucent or opaque records with a maximum width of 12 inches and a minimum width determined by the adequacy of the magnification of 2.5:1 for the record in question. It provides means for accurately measuring distance on the records along two orthogonal axes, permitting rapid and convenient transmission of data from records to digital numbers representing deflections from an arbitrary fixed reference. It incorporates the necessary equipment for supporting and transporting the record; for magnifying and projecting a section of the record, along with the measuring cross wires, on a viewing screen; and for indicating the position of the cross wires by mechanical counters. The Telecorder, in conjunction with an IBM Summary Punch, permits recording of the cross wire positions in standard IBM cards.

The combination of Telereader, Telecorder, and Summary Punch is capable of punching IBM cards at a maximum rate of 50 per minute. With this combination the reproducibility of the measuring system of the Telereader is

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* - Manufactured by the Telecomputing Corporation, 133 E. Santa Anita Avenue, Burbank, California.

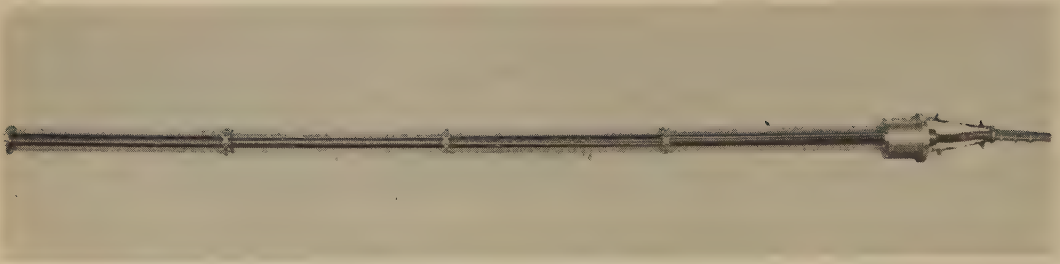

Fig. 7. 10-Foot Line Hydrophone

At the Underwater Sound Laboratory we have encountered certain situations where sound propagation conditions as predicted on the basis of ray theory and the bathythermogram are by no means realized. In these situations a well mixed surface layer was present. Propagation in the surface layer should have been good; it was very poor. In such situations the very great importance of small thermal gradients has been pointed out. It seems entirely possible that under certain conditions current gradients may exist which have an equally important effect. Instrumentation and methods for measurement of current gradient with depth will be welcomed by both the acoustician and the oceanographer.

DISCUSSION: Leonard Liebermann

I believe it is worth pointing out that Dr. Hersey's excellent and comprehensive discussion of "Acoustic Instrumentation for Oceanography" has been presented on the framework of existing acoustic instruments and their applications to oceanography. He has preferred to set the emphasis on acoustic equipment with possible applications, rather than primarily on the oceanography. Suppose instead of this viewpoint, one begins with the important contemporary problems of oceanography; and inquires what contributions, if any, might be made by applying acoustic techniques to these problems. Two major oceanographic problems immediately come to mind: the study of the dynamics of ocean currents and the study of ocean waves and their prediction.

Beginning with the first problem, one of the obstacles to the study of ocean currents is the difficulty with which field observations can be made; the ideal current meter has not yet been invented. However, acoustical techniques make it possible to measure doppler frequencies caused by relatively slow velocities. Hence, it now appears feasible to construct echo ranging equipment designed to measure ocean currents. Comparison of the frequency of the bottom echo with the reverberation frequency from the body of the ocean water would yield the current velocity. In this manner it may actually be possible to delineate ocean currents at different depths. An important advantage would be the possibility of continuous measurements while the ship was under way. The same equipment may also be used for the accurate determination of relative ship's motion.

Another closely related problem is the determination of total water mass flow, in various parts of the ocean. Stommel has made observations on the flow of the Gulf Stream through the Straits of Florida. He observed the induced voltage in a pair of electrodes fixed at opposite sides of the stream. However, his technique is limited in the choice of locations because the two electrodes must be electrically connected; in this case by means of a commercial submarine cable.

Acoustics offers an alternative scheme which does not require a cable. Two hydrophones suspended from two ships would be placed on the bottom, on a line in the direction of the current to be observed. By means of a radio-link, underwater shots would be fired simultaneously (or at a known interval) at the two hydrophone locations. The difference in travel time in the two directions would give the current velocity. For example, if the ships are one mile apart the difference in arrival time is approximately 0.7 milliseconds for each knot of current. Time differences at this range can readily be measured to better than 100 microseconds. If sound transmission paths via several bottom-surface reflections are utilized for the time measurement, the observed current velocity would represent a form of average current from surface to bottom. This observation would probably be most suitable for calculation of the total mass flow. Other sound transmission paths could be selected for additional ocean current information.

Contribution to the study of ocean waves might be made by applying acoustic techniques. Substitution of an inverted echo sounder for the conventional wave meter has already been successfully tried. However, this kind of measurement yields only the time dependent displacement of the sea surface overhead. More important would be an observation of the instantaneous spatial distribution of the waves. Eckart has shown that the spatial distribution of the waves may be characterized statistically by the spatial auto-correlation function of the sea surface. This characteristic function can be obtained in principle by echo-ranging on the sea surface. Choice of echo-ranging frequency would be determined by the period of surface waves of interest. Thus, if surface waves of length 10 feet are of interest, the echo-ranging frequency should be in the neighborhood of 500 cycles.

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Contribution No. 698

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Underwater Explosion Shock Wave Parameters at Large Distances from the Charge*

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(Received September 9, 1953)

Experimental observations of peak pressure, decay constant, and energy flux for TNT and pentolite are presented to ranges (in feet) defined by $R \cong 2000W^{1/3}$, where W is charge weight in pounds. Previously published results extended only to $R \cong 30W^{1/3}$.

1. INTRODUCTION

1.1 A series of experimental measurements, with explosives TNT and pentolite, has been made to extend the knowledge of underwater shock wave parameters to distances from the charge greater than those hitherto reported.[1] These results are shown (together with earlier work[1] by Coles *et al.*) in the form of similarity curves in Fig. 1, 2, and 3.

2. PEAK PRESSURE-DISTANCE DECAY

2.1 Available experimental peak pressures, for about three and a half logarithmic cycles of pressure and

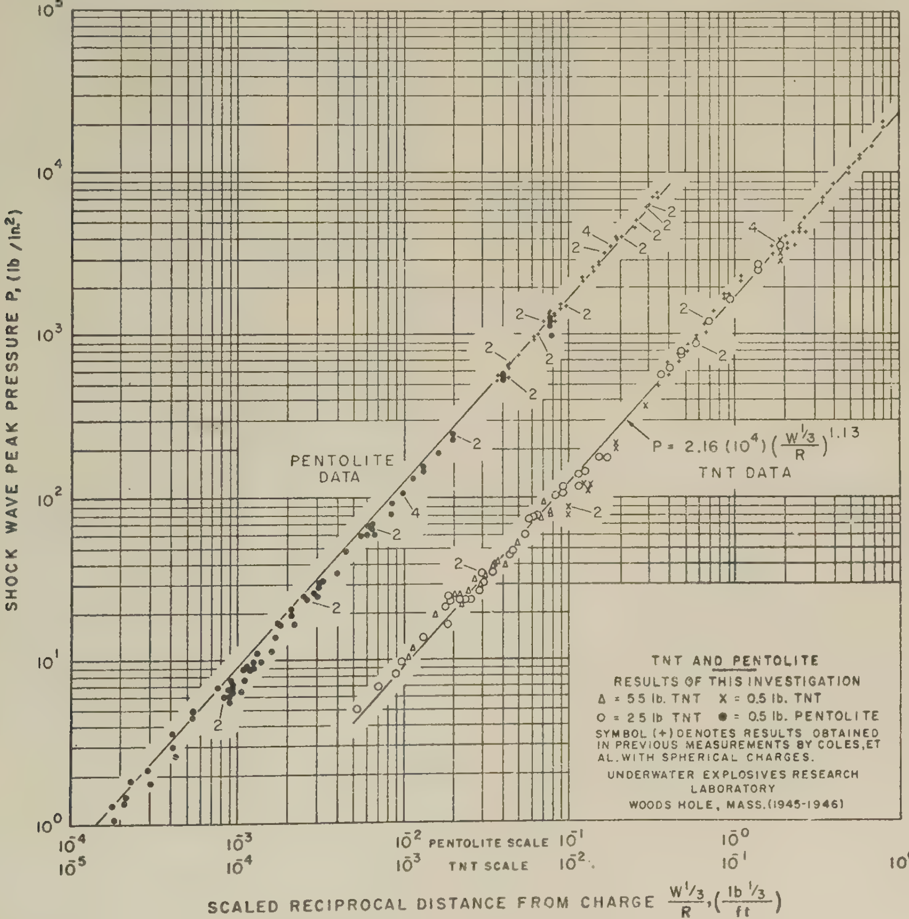

Fig. 1. Shock wave peak pressure *vs* scaled reciprocal distance.

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* Contribution No. 698 Woods Hole Oceanographic Institution. Results of work performed under contract with the U. S. Navy Department, Bureau of Ordnance.

[1] R. H. Cole, *Underwater Explosions* (Princeton University Press, Princeton, New Jersey, 1948).

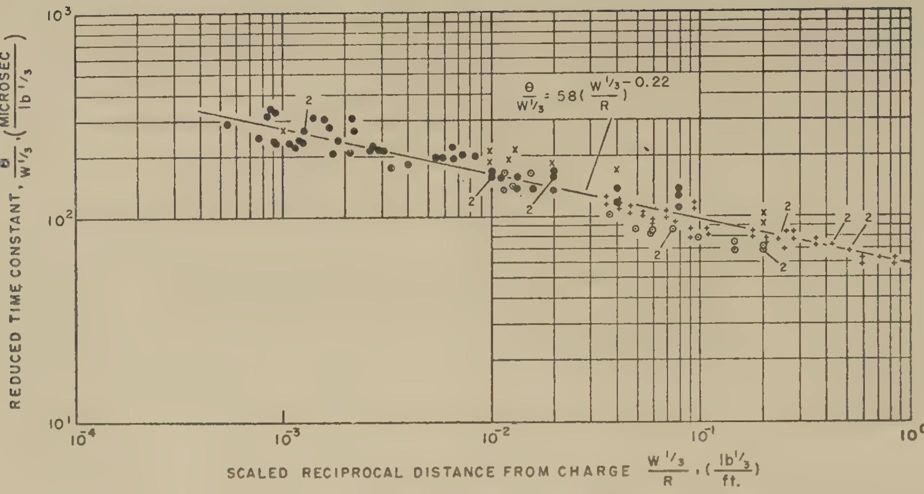

FIG. 2. Reduced shock wave time constant *vs* scaled reciprocal distance from charge TNT and pentolite (see Fig. 1 for code symbols).

distance, are shown in Fig. 1. The more reliable data are probably those for TNT since most of the measurements were obtained with charges of from 25 to 76 lb whereas, in the case of pentolite, some of the close range and all of the long range data were obtained with small charges. Errors owing to instrumental response (see Section 5) usually cause results for small charges (*ca* 0.5 lb) to fall significantly below similarity curves based on larger charge results even when approximate correction for instrumental response is introduced, and this effect is quite apparent for the 0.5-lb TNT charges in Fig. 1.

2.2 The most striking aspect of Fig. 1 is the way in which the power function of slope 1.13, originally observed in the close range data, persists over more than three logarithmic cycles of the variables, and gives no evidence of significant change toward a slope of unity even at the lowest pressures observed.

Ideal acoustic theory, which does not consider dissipative or finite amplitude effects, requires a slope of 1.00, i.e., a pressure decay inversely proportional to distance. The departure of observed slope from unity is recognized as the result of dissipation of energy and of spread of the profile of the wave, and in the pressure range above the order of 100 lb/in.^{2}, the Kirkwood-Bethe theory[1] accounts quite well for the observed slope of 1.13. In this range the dissipation arises principally in the irreversible compression at the shock front itself.

2.3 For longer ranges, however, the Kirkwood-Bethe theory yields an asymptotic peak pressure-distance dependence (reference 1, p. 126) of the form

$$P \sim \frac{a_0}{R} \log \frac{R}{a_0}, \qquad (1)$$

where a_0 denotes charge radius.

2.4 When the logarithmic term of Eq. (1), properly converted, is plotted for the range $0.0002 < W^{1/3}/R < 0.005$ of Fig. 1, a line with slight upward curvature is obtained. The line, within the range indicated, can be approximately represented by a power function of slope 0.06, which measures the departure from unit slope. The net result is significantly less than the observed value of 1.13.

3. SPREAD OF THE PROFILE

3.1 Figure 2, a plot of decay constant *vs* $W^{1/3}/R$, shows how the profile of the wave continues to spread with increasing range.

3.2 Unfortunately, the present investigation did not yield direct quantitative information with respect to changes in rise time of the wave front. The sensitivity of the recording instruments was such that it was necessary to keep using larger size tourmaline gauges with increasing distance from the charge in order to maintain adequate signal strength. Since the records always showed a rise approximately equal to the gauge transit time, we conclude that the true rise time must be less than that of gauge transit, which for the largest gauges, was about 30 microseconds.

4. IMPULSE AND ENERGY FLUX

4.1 Figure 3 shows the observed results with respect to impulse and energy flux for the explosive pentolite, which is not very different in its parameters from TNT. It will be noted that the long range results fall on power functions which are the extensions of previous observations. The constancy of slope of impulse and energy flux is consistent with the constant slopes of the pressure and decay constant observations.

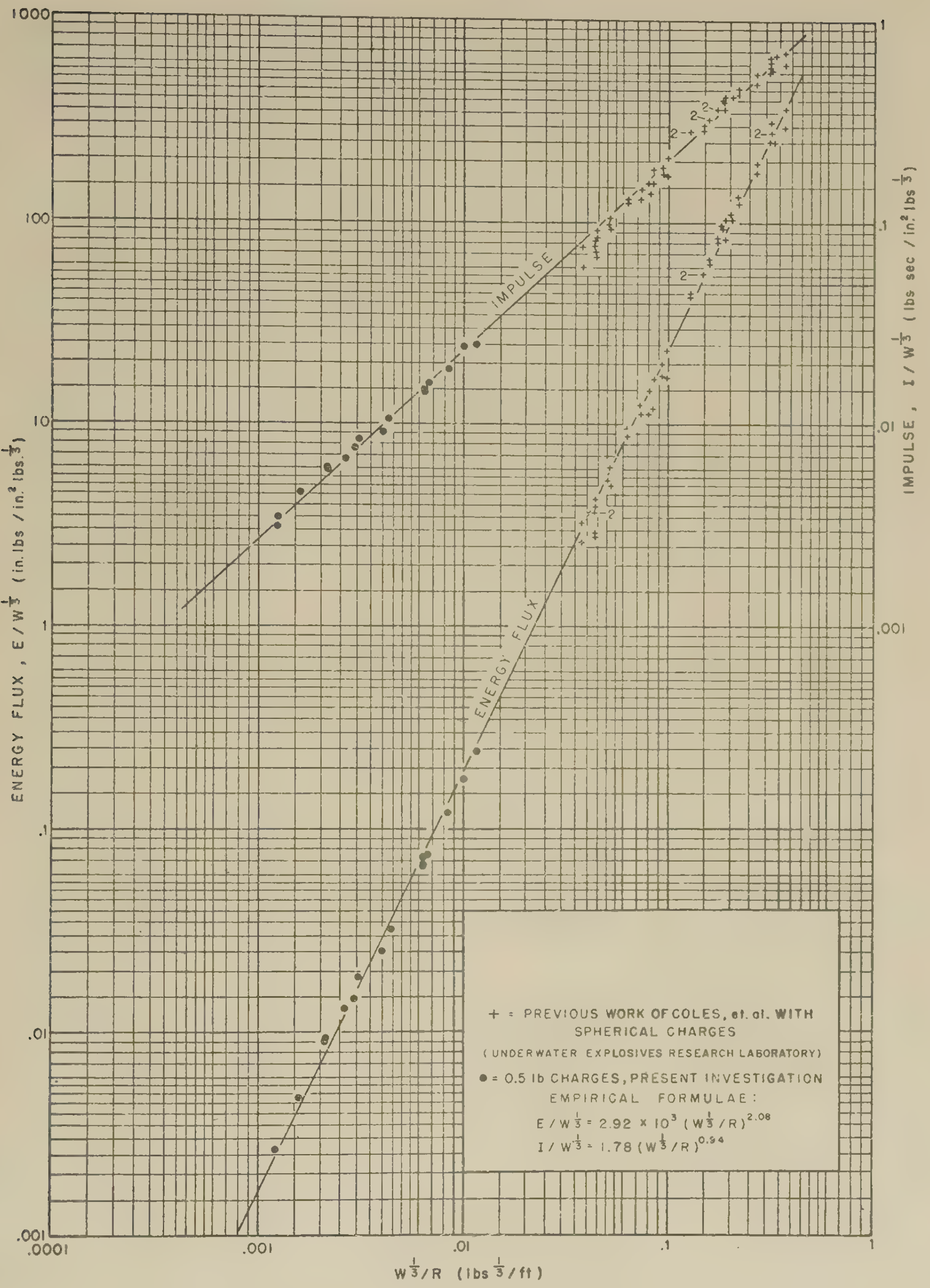

FIG. 3. Reduced energy flux and impulse *vs* $W^{\frac{1}{3}}/R$. Explosive: pentolite.

5. EXPERIMENTAL TECHNIQUES

5.1 All the experimental results reported in this paper are based on the analysis of oscillographically recorded pressure-time curves obtained with electronic systems[1] and tourmaline gauge techniques[1,2] developed at the Underwater Explosives Research Laboratory,

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[2] A. B. Arons and R. H. Cole, Rev. Sci. Instr. 21, 31 (1950).

Woods Hole Oceanographic Institution, Woods Hole, Mass. during World War II.

Oscilloscope records were made on rotating drum cameras, giving a time resolution of approximately one millisecond per inch of film. Each pressure point plotted is the average of three values obtained from three separate gauge records at each point of observation. Peak pressure readings were corrected for gauge size effects in accordance with the discussion given in reference 2.

5.2 Charge to gauge distances were obtained by means of a fourth recording channel utilizing a slowly turning drum camera in the following manner: The firing line current was used to key an FM transmitter on the small boat which was used to set and fire the charges. The transmitted signal unblanked the spot on the ranging oscilloscope aboard the recording vessel, and a hydrophone, set a few feet ahead of the gauges suspended over the side of the vessel, recorded the arrival of the pressure wave on the same channel. The elapsed time between unblanking of the spot and arrival of the wave at the recording vessel (corrected for the measured time delay inherent in the over-all system) was used, together with sound velocity for the measured conditions of water temperature and salinity, to compute the charge to gauge distance. Experiments were performed in well mixed tidal waters in Vineyard Sound, and refraction effects were known to be negligible. The ranges thus obtained are believed accurate to about 2 percent.

5.3 The absolute level of the close range peak pressure results (shown in Fig. 1 as having been previously obtained) had been independently checked by means of mechanical (ball crusher) gauges to within 3 percent.

6. ACKNOWLEDGMENT

6.1 The author wishes to acknowledge the valuable assistance of Mr. Wolfgang Grube and Mr. A. C. Redfield, Jr., and of Mrs. Nellie Andersen in the experimental work.

Contribution No. 699

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Printed in U. S. A.

SECRETION OF GASES AGAINST HIGH PRESSURES IN THE SWIMBLADDER OF DEEP SEA FISHES.

I. OXYGEN DISSOCIATION IN BLOOD[1]

P. F. SCHOLANDER AND L. VAN DAM

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, and Lerner Marine Laboratory, Bimini, Bahamas

By studying the composition of the swimbladder gases in relation to depth it was established that both oxygen and nitrogen are deposited into the swimbladder against a concentration gradient to make up the hydrostatic pressure. The nitrogen is deposited as a certain fraction of the oxygen varying from 2 to 15%, according to the species. Carbon dioxide and organic gases contribute only insignificantly to the pressure. The oxygen pressure commonly reaches values above 100 atmospheres, and it is likely that it can be two to three times as much, as species with swimbladders are known to occur down to a pressure of at least 266 atmospheres. The nitrogen pressure in deep sea species frequently reaches 10–15 atmospheres (Scholander and van Dam, 1953).[2] In whitefish (*Coregonus*) pure nitrogen may be deposited into the swimbladder against 6–8 atmospheres' pressure (Hüfner, 1892). Saunders (1953) has verified this finding, and has added four more species of physostome fresh water fishes which also seem to deposit nothing but nitrogen in the swimbladder.

CURRENT THEORIES OF GAS SECRETION

Haldane (1922) in his celebrated book "Respiration" gives his views as to a possible mechanism for the gas secretion, which in its basic concepts expresses the ideas offered by later authors. He saw in the *rete mirabile* a counter current exchange mechanism (p. 214): "The arrangement reminds us of that in a regenerating furnace, where the heat carried away in the waste gases is utilized to heat the incoming air." As to the chemical release of oxygen he points out the importance of CO_2 in expelling oxygen from the hemoglobin and states (p. 215): "It seems probable, therefore, that the function of the *rete mirabile* is to enable venous blood to communicate part of its CO_2 to the arterial blood. The effect of this will be to raise the CO_2 pressure of the blood supplied to the gland, and so raise the oxygen pressure." Already Müller (1840) and Woodland (1911), who presented accurate anatomical drawings of the *rete,* had considered that they must be interpreted as a diffusion apparatus between the arterial and venous capillaries.

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[1] Contribution No. 699 from the Woods Hole Oceanographic Institution. This investigation was supported by a grant from the National Science Foundation.

[2] In our 1953 paper data are given on gas samples from *Alepocephalus* and *Cottunculus*. From the excellent review of Jones and Marshall (1953) we learned that *Alepocephalus* does not have a swimbladder and this we verified on our recent material. We found also that *Cottunculus* has no swimbladder. This raises the question as to where the gas came from of which we obtained a few cubic centimeters by poking around in these fishes with our needle. The presence of the gas was obvious because the fishes were floating on the water. The composition of this gas checked well with that of the other fishes in the same catch, and hence it is believed that the fish must have swallowed some of the gas gushing out from other fishes when the trawlbag approached the surface. Obviously a fish distended by swimbladder gas cannot pollute this gas by swallowing.

Hall (1924) found that, if the gas gland in yellow perch (*Perca flavescens*) was stimulated to activity by removing gas from the swimbladder or by increasing the hydrostatic pressure, a dialysate of the active gland showed a decrease in pH from 7.1 to 6.4, as compared with a non-active gland. He assumed secretion of an acid by the glandular epithelium. This would diffuse into the capillaries of the *rete* and by releasing bound oxygen would raise the oxygen tension, permitting the oxygen to diffuse into the swimbladder. If the oxygen capacity were 9 vol. % and the solubility coefficient 3 vol. % per atmosphere, then this mechanism could raise the oxygen tension no more than 3 atmospheres. This would be ample for shallow water fish like the perch, but could not explain the secretion of 100 atmospheres or more in deep sea fishes.

Jacobs (1930) found a way out of this difficulty by elaborating somewhat further on the possible function of the *rete mirabile.* When acid is secreted by the glandular cells and diffuses into the blood, CO_2 is released, increasing the CO_2 tension. The CO_2 effect itself, or possibly the secreted acid, dissociates oxygen from the oxyhemoglobin, so that both CO_2 and oxygen tension increase. This would explain the fact that both O_2 and CO_2 tension increase when gas is generated following a puncture. The blood with elevated O_2 and CO_2 tension leaves the gland and enters the efferent (venous) *rete,* where the gases diffuse over to the afferent (arterial) side, boosting the tensions there. When this high tension blood enters the gland, new acid is added, the tensions are again stepped up, and so on, until high enough tension has been built up in the swimbladder.

The secretion of oxygen would accordingly involve two principal steps: (1) a chemical dissociation of oxygen by acid (and/or CO_2) from the oxyhemoglobin, and (2) a counter current exchange mechanism (the *rete mirabile*) which would retain the secreted gases within the swimbladder with a minimal loss to the outside, in spite of maintained circulation. These basic ideas have been accepted by almost all later workers as the likely mechanism for oxygen secretion in fishes (Powers *et al.,* 1932; Koch, 1934; Irving and Grinnell, 1939; Black, 1946; Copeland, 1952; Strittmatter, Ball and Cooper, 1952; Fänge, 1953). Von Ledebur (1937) expressed serious doubts as to the correctness of the chemical interpretation.

In the present account we shall deal with the oxygen dissociation at pressures from 0.2 to 140 atmospheres and its relation to pH and CO_2. The function of the *rete mirabile* will be dealt with in a later account.

OXYGEN DISSOCIATION IN BLOOD FROM DEEP SEA FISHES IN RELATION TO pH AND CO_2

The chemical or physical reaction which is in the end responsible for the oxygen deposition in deep sea fishes must be able to perform against a pressure which at least equals the partial pressure of oxygen known to occur in the fish in question. Many deep sea fishes secrete oxygen against 100 atmospheres or more, and by inference some secrete against considerably more than 200 atmospheres.

It has long been known that the blood of many fishes possesses a large Bohr effect (Krogh and Leitch, 1919, and many later authors). Root (1931) and Green and Root (1933) found that in several fishes the blood did not become completely saturated if acid or CO_2 was added at oxygen pressures up to near one atmosphere. The saturation curves were found to run virtually horizontal at pressures above 0.5 atmosphere. The *Bohr effect* is generally considered a change in the dissociation constant (K in the Hill equation) with 100% saturation obtainable at high enough pressure. The term *Root effect,* on the contrary, may be reserved for the situation where acidity completely blocks the oxygen from part of the hemoglobin.

Obviously, before we can know whether the Bohr or Root effect can be responsible for the oxygen secretion against 100–200 atmospheres' pressure, we must extend the dissociation curves to these pressures. This has been done for a series of ocean fishes inhabiting depths equivalent to pressures from 40 to as much as 260 atmospheres.

The investigation was commenced in the winter of 1952–1953 at the Lerner Marine Laboratory, Bimini, Bahamas, and was amplified by material caught on the dragger *Cap'n Bill II* during two cruises in the summer of 1953 off the New England coast.

Material

Fishes were caught at the bottom by hook and cable from 400–700 meters' depth in the Gulf Stream off Bimini between December, 1952 and February, 1953. For this purpose a gasoline-powered fishing rig was used, originally designed by Captain Eddie Wall at the Lerner Laboratory. The fishes were brought to the surface within 4–7 minutes after hooking, according to the depth. Blood was drawn immediately by hypodermic needle from the heart and transferred to a polyethylene bottle containing a little heparin. The sample, of about 20–50 cc., was stored on ice and brought to the laboratory within an hour. The blood was then put through all the necessary procedures at once.

Three species were obtained at Bimini:

			Depth of catch
3	*Epinephelus mystacinus*	Black grouper	320–400 m.
1	*Alphestes* sp.[3]	"Golden grouper"	410 m.
2	*Polyprion americanus*	Wreckfish	640 and 675 m.

The fishes weighed between 10 and 30 kg. each.

Deep sea material was likewise obtained on board the dragger *Cap'n Bill II,* operating from Woods Hole, on two cruises (June 16–23 and July 1–8, 1953). The fishes were caught by bottom trawl, mostly at depths of between 500 and 1300 meters, depending upon the species. It took up to three quarters of an hour to get the trawl to the surface from the time it left the bottom. The blood could in some cases be drawn from the heart (*Sebastes*). In other cases blood was obtained which dripped from the cut tail. It was usually necessary to pool blood from many specimens to get enough for the analyses, which were performed immediately.

[3] Called *Epinephelus,* Grouper, in Scholander and van Dam (1953).

The following species were caught and analyzed on the *Cap'n Bill:*

		Depth of catch
Antimora viola	Blue hake	1200 m.
Coryphaenoides rupestris	Round-nosed ratfish	1100 m.
Sebastes marinus[4]	Rosefish	550– 720 m.
Synaphobranchus pinnatus	Long-nosed eel	960–1100 m.
Urophycis chesteri	Long-finned hake	600–1300 m.

Optical method for determination of dissociation curves at high pressures

The problem required a study of oxygen dissociation of fish blood at different pH or CO_2 tensions carried from an oxygen pressure of 0.2 atmosphere, if possible, up to values corresponding to the greatest depth at which the species was known to occur. As a routine the highest oxygen pressure employed was that of a fully charged commercial gas cylinder, *i.e.,* 140 atmospheres.

An earlier survey (van Dam and Scholander, 1953) showed that the blood of deep sea fishes had about the same oxygen combining capacity as that of shallow fishes, *i.e.,* about 6–10 vol. %. At 100 atmospheres' pressure the blood would physically dissolve about 300–400 vol. % oxygen, and hence it would be impossible by direct gasometric methods to determine the saturation of the hemoglobin. An optical method was therefore designed.

The method must be accurate to within a few per cent saturation, and it must be possible to operate it on a rolling ship. It was necessary to equilibrate the blood sample in the photometer cuvette, which must be accurately controlled to the same temperature as that at which the bottom fishes live. The cuvette must be able without significant distortion to stand a pressure of 140 atmospheres.

As a measuring instrument a Zeiss Pulfrich Stufen Photometer[5] was employed. The construction of the high pressure cuvette will be seen in Figure 1. The glass windows were ½-inch thick and the effective depth of the blood in the optical paths was 1.6 mm., increasing 1% at 140 atmospheres. Sealing of the cuvette chamber was obtained by a Neoprene "O" ring squeezed between the windows. Entrance to the cell was by means of a number 20 hypodermic needle which pierced the "O" ring. Through this needle blood could be introduced by a number 25 needle. The cell could be cleaned by rinsing it with 0.17 *M* saline solution, which was then removed by suction. A stainless steel ball was kept in the cuvette for stirring. The cuvette was dropped into an insulated water bath occupying the position where ordinarily the cuvette holder is placed on the instrument. Water of constant temperature (4° or 10° ± 0.1° C.) circulated through the water bath. Dewing of the water bath windows was prevented by keeping them wet with soap solution. To accomplish equilibration the cuvette was only partially filled with blood (see Fig. 1), and it was rotated back and forth through an arc of 45° by means of a motor. To permit rotation the high pressure line of small gauge copper tubing was wound as a loose helix around the cuvette water bath, seven to eight turns, before it was connected to the oxygen cylinder. The oxygen pressure was regulated by means of a long handle on the main oxygen valve, and the pressure was read on a conventional high pressure gauge (10–140 atm.). Between one and 10 atmospheres the pressure was read on a special low pressure gauge, which could be shut off from the main line at pressures above 10 atmospheres. The "O" ring was always kept wet when under oxygen pressure and so far has not exploded.

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[4] In the paper of Scholander and van Dam (1953) the maximum depth of *Sebastes* is given as 1680 m., as recalculated from 917 fathoms given in Goode and Bean (1895, p. 261). This, however, represents a misquotation of the original figure of 179 fathoms (Townsend, 1901, p. 398).

[5] This was kindly lent to us by the Department of Biological Chemistry, Harvard Medical School.

The extinction of the blood at various oxygen tensions was read through a Wratten red filter, number 29F, and was compared with a constant gray filter held in a dry dummy-cuvette on the other side. This red filter gives the greatest separation between the oxy- and reduced hemoglobin. A gray filter (from a series of variously exposed photographic negatives) was chosen which gave a suitable reading for the oxygenated blood. As the light path on both sides was restricted to a diameter of one quarter of an inch, no wider diaphragm openings could be used than those corresponding to 0.50 on the extinction scale. The reading from full oxygenation to full reduction usually went from around 0.50 to about 1.20–1.30, giving a resolution of this extinction interval of about 2%.

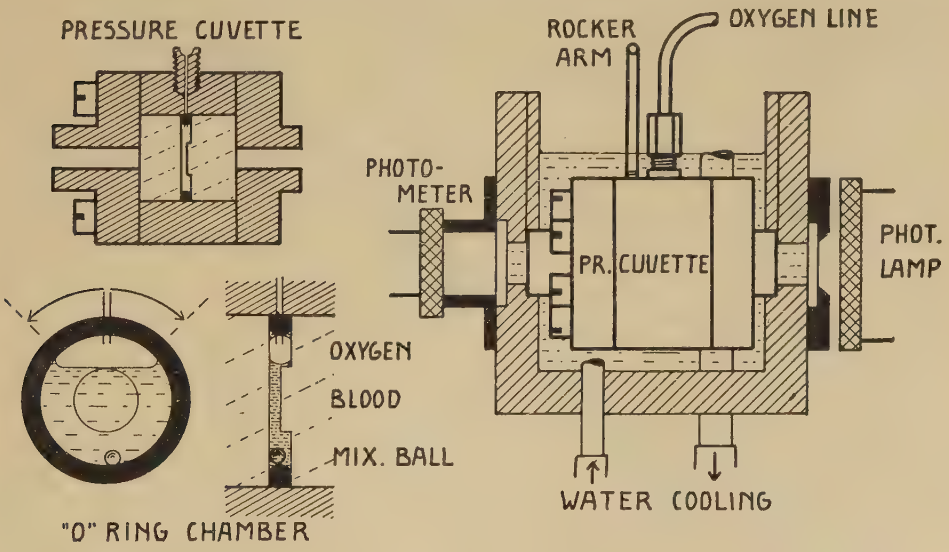

FIGURE 1. Cuvette arrangement for a study of high pressure dissociation curves.

Procedure

The heparinized blood, kept on ice, was strained, if necessary, through a few layers of gauze. Blood was transferred into three 20-cc. Erlenmeyer flasks, A, B, and C, 3.0 cc. in each. To A was added 0.3 cc. 0.17 *M* NaCl. To C the same amount of 0.17 *M* lactic acid solution was added very slowly while agitating the blood. To B was added 0.3 cc. of an equal mixture of 0.17 *M* NaCl and 0.17 *M* lactic acid. Samples A, B, and C hence contained 0, 8, and 16 millimols added lactic acid. This would drop the pH from A to B by approximately 0.7 pH units and from A to C by approximately 1.5 units. The flasks were provided with stoppers pierced with a glass tubing 6 inches long, open at both ends. They were then rotated in a water bath of the desired temperature (10° or 4° C.). A fine suction tube was passed frequently into the flask through the glass tubing to renew the air. After about 20 minutes the blood would be well aerated. Sample A was taken out and its pH taken on a Cambridge Electron Ray pH Meter. The cuvette was provided with a water jacket to keep the blood at the desired temperature. If it was below about 7.4 a small known amount of NaOH would be added very carefully until a pH of about 7.6—7.8 was obtained. The flask was rotated again and the blood was then transferred to the pressure cuvette, which meanwhile had been temperature-equilibrated in its water bath on the photometer. Rocking of the cuvette was started, and the extinction was read as soon as a constant reading could be obtained. The oxygen line was flushed and connected with the cuvette and the pressure set to give one atmosphere O_2 in the cuvette (= 1.8 atm. total).

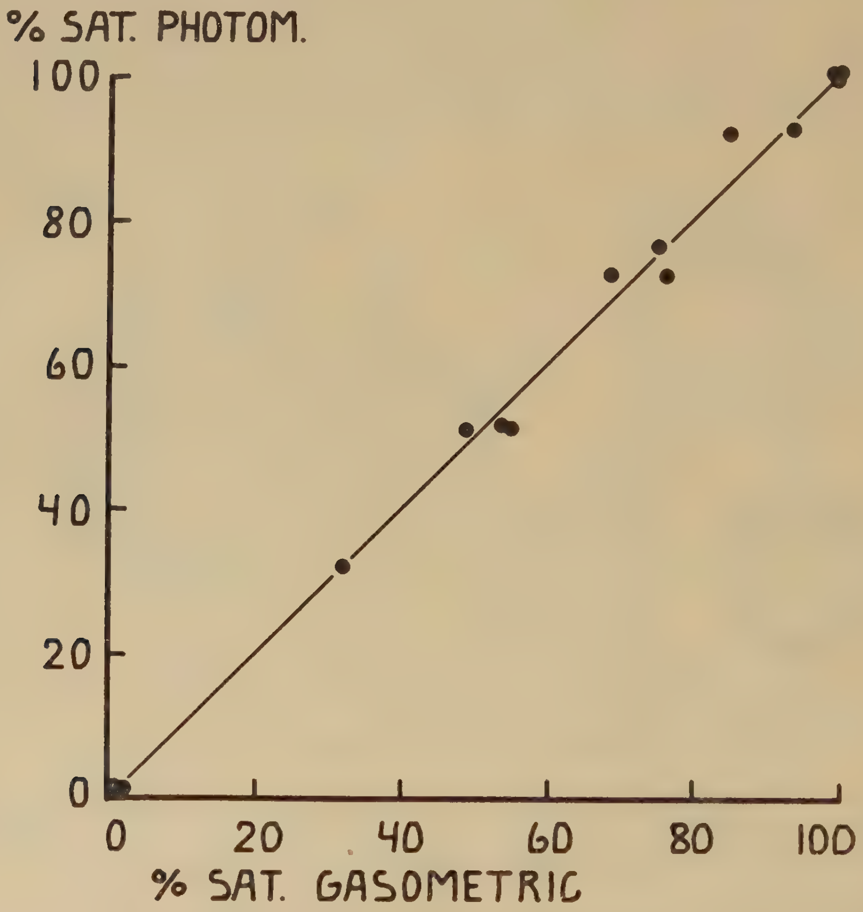

FIGURE 2. Correlation between optical and gasometric determinations of the oxygen saturation in the blood of tautog.

After about 5–10 minutes' equilibration the reading would be constant, and the pressure was raised to two atmospheres' O_2 (= 2.8 atm. total) and so on. Our oxygen contained less than 0.01% CO_2 and 0.02% N_2.

Meanwhile the remainder of sample A (about 2 cc.) was put in a rotating 50-cc. syringe, which was repeatedly flushed with helium (containing less than 0.01% O_2) for reduction of the hemoglobin. The helium was ejected and replaced four or five times, during a total equilibration time of about three quarters of an hour.

The pressure-equilibrated blood was removed from the cuvette by suction, and the cuvette thoroughly rinsed with cold 0.17 *M* saline. It was then flushed with helium and the reduced blood was introduced, completely filling the cuvette, without any contact with air. The rocker was started and the extinction of the reduced blood read.

Sample B was now taken from the equilibrator, part of it transferred to the pressure cuvette, and part of it to the pH meter. The whole procedure was then repeated for B and finally for sample C. The oxygen saturation was calculated by taking the fully saturated reading as 100% and the reduced as 0%, interpolating the intermediary readings according to a linear relation which had been found to hold for tautog blood (Fig. 2).

In cases where the effect of various CO_2 tensions was tested (at Bimini only), CO_2 and air mixtures were made up in a small spirometer and accurately analyzed (Scholander, 1947). The sample was equilibrated in a 50-cc. rotating syringe with this gas mixture, which was changed four or five times. Concentrations of 5, 10, and 20% CO_2 were used, accurate to ± 0.1%. The cuvette was flushed with the proper gas mixture before it was filled with blood.

Although optical determinations of the saturation are satisfactory enough when dealing with the same blood sample, they may not be so satisfactory when comparing samples of different pH. It is not too easy to get an accurately fixed zero point for the reduced blood. Hydrosulfite as a reductant is unsuitable to use, as the blood gets darker and darker the more hydrosulfite is added. Vacuum technique involves much shaking and handling of the delicate fish blood, and easily gives evaporation errors. We have obtained most constant results by equilibrating with helium (99.99% pure). But even so, it seems that at least sometimes a change in pH by careful titration with lactic acid will change the light transmission somewhat, due to such things as change (increase) in cell size or slight degree of hemolysis and fibrin formation. We do not believe that this source of error can have seriously distorted our results, but it is likely to be the cause of much of the spread in our data. In most cases the extinction readings of the reduced blood have matched each other within a few per cent at the different pH, and nearly always the fully oxygenated values have checked each other at different pH. The latter is the most important in the present connection.

As to the acidification of the blood we know in each case exactly the amount of acid added. The pH determinations were always made in aerated samples. A certain amount of drift and unsteadiness in the pH meter seemed unavoidable when it was used on our rolling moisture-laden ship, although the meter was kept in a dry-chamber. However, the fact that the drop in pH induced by the added known amounts of acid always came out with satisfactory regularity, as well as the fact that a colorimetric method used on our last cruise gave identical results,

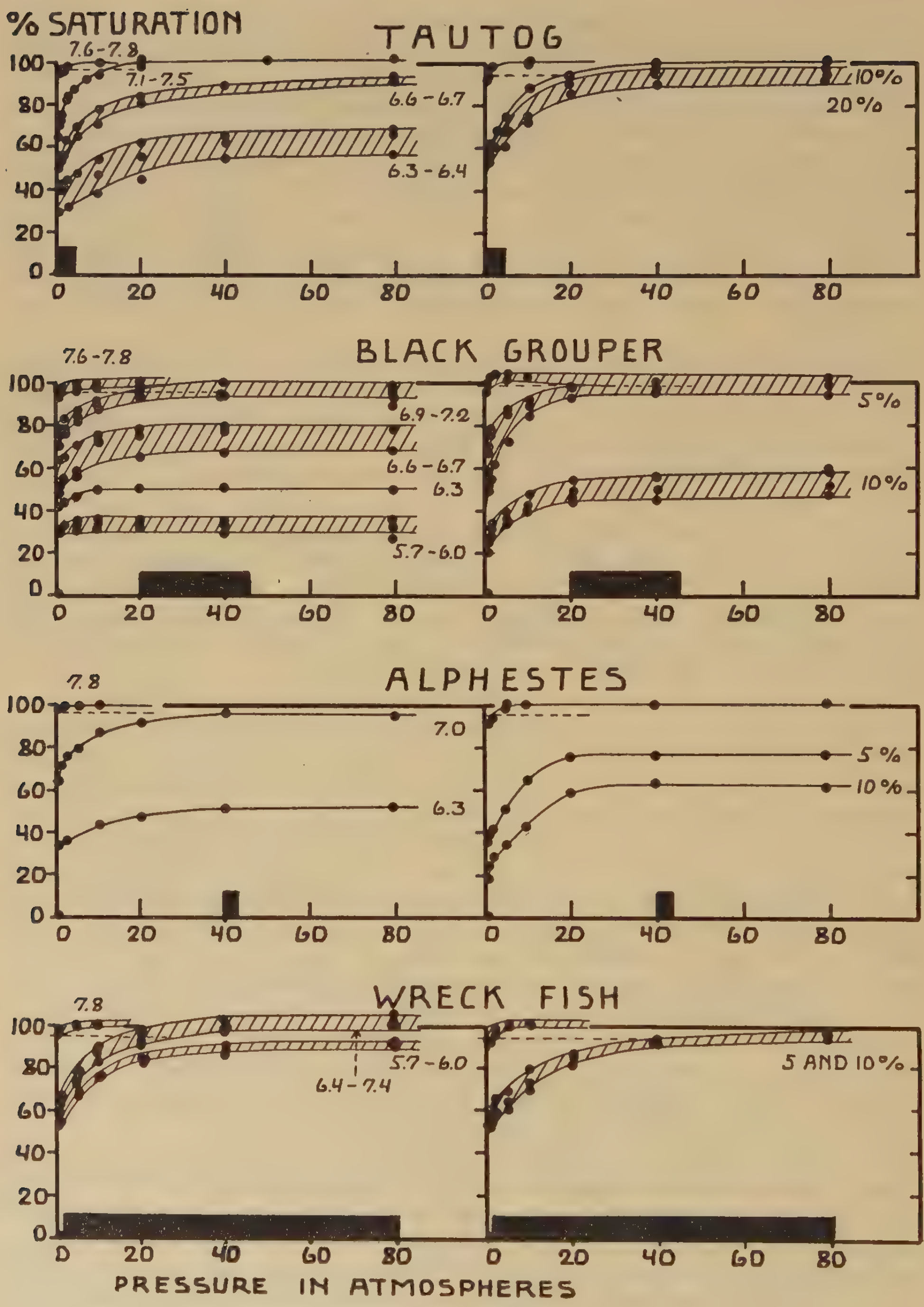

FIGURE 3. Oxygen saturation curves in various fishes at 10° C. Lactic acid was added to the blood in the curves on the left, CO_2 in those on the right. The pH values are given for curves of the lactic acid series. The equilibration pressure of CO_2 is given as per cent of one

lend assurance that our pH measurements must have been essentially correct. From very frequent checks back to our buffer standards, we consider our pH measurements to be reliable to within ± 0.1 pH unit.

RESULTS

In Figures 3 and 4 the oxygen dissociation curves are plotted for fishes living from shallow surface waters to the abysmal depths. The curves span a range of pH from 8.0 to 5.6, and the carbon dioxide tensions used were 0.03, 5, 10, and 20% of an atmosphere.

It will be seen that in half of the eight species of deep sea fishes investigated (grouper, *Alphestes,* long-finned hake, ratfish) lactic acid in a concentration of about 100–150 mg. % (pH 6.7—5.6) produces a clear Root effect, in that the hemoglobin does not become more than 30–80% saturated at tensions as high as 140 atmospheres.[6] The curves run horizontal from above 20 to 30 atmospheres. In these cases, therefore, the Root effect could be responsible for the oxygen secretion.

In the remaining four deep sea species (rosefish, wreckfish, blue hake, long-nosed eel), however, even at pH 6 the hemoglobin became 90% or more saturated when the pressure exceeded 50–100 atmospheres. The arterial saturation at 0.2 atmosphere is no more than 90–95% at pH 7.6—7.8. Since the oxygen tension in the swimbladder frequently exceeds 50–100 atmospheres it appears impossible that the Root effect can account for gas secretion in these cases, unless possibly the pH falls below 5.6—6 in the blood vessels of the gland.

It seems dubious that the pH in the blood could ever reach such a low value as 6.0. If we consider pH 6.5 as the lowest physiological limit, then only the black grouper and possibly *Alphestes* would be able to maintain part of the hemoglobin in a reduced state in the presence of the high oxygen tension. Of course we do not know what the pH might be in the capillary blood passing through the gland. The lowest pH found in the blood of dead asphyxiated fishes was 6.9. At the highest acidity used *in vitro* it was impossible to avoid the precipitation of some fibrin, and hemolysis occurred with the addition of very little more acid.

If a high CO_2 tension were to be considered responsible for the oxygen secretion via the Root effect, then the CO_2 must be present at high concentrations in the blood vessels of the gland in which case it would diffuse with the oxygen into the bladder where its concentration can be measured. In shallow fishes swimbladder CO_2 is usually below 1–2% (Table I). In the wreckfish the oxygen secretion could not be explained by the Root effect unless the CO_2 were more than 10% of an atmosphere, and the tautog would require more than 20% CO_2 to secrete in deep water. Accurate determinations were made of the CO_2 tension in the swim-

[6] The Root effect was described from blood of shallow water fishes, dealing with oxygen pressures of no more than 700 mm. Hg (Root, 1931).

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atmosphere. The broken line (90–95% saturation) denotes the arterial saturation at 0.2 atmosphere O_2 pressure. The solid bar on the base line is the range of depth in atmospheres where these species live. For each range of pH or CO_2, 3 or 4 separate runs with different bloods were usually made to get an impression of the individual variability. All curves were continued to 140 atmospheres' oxygen pressure, but showed no change from the values at 80 atmospheres.

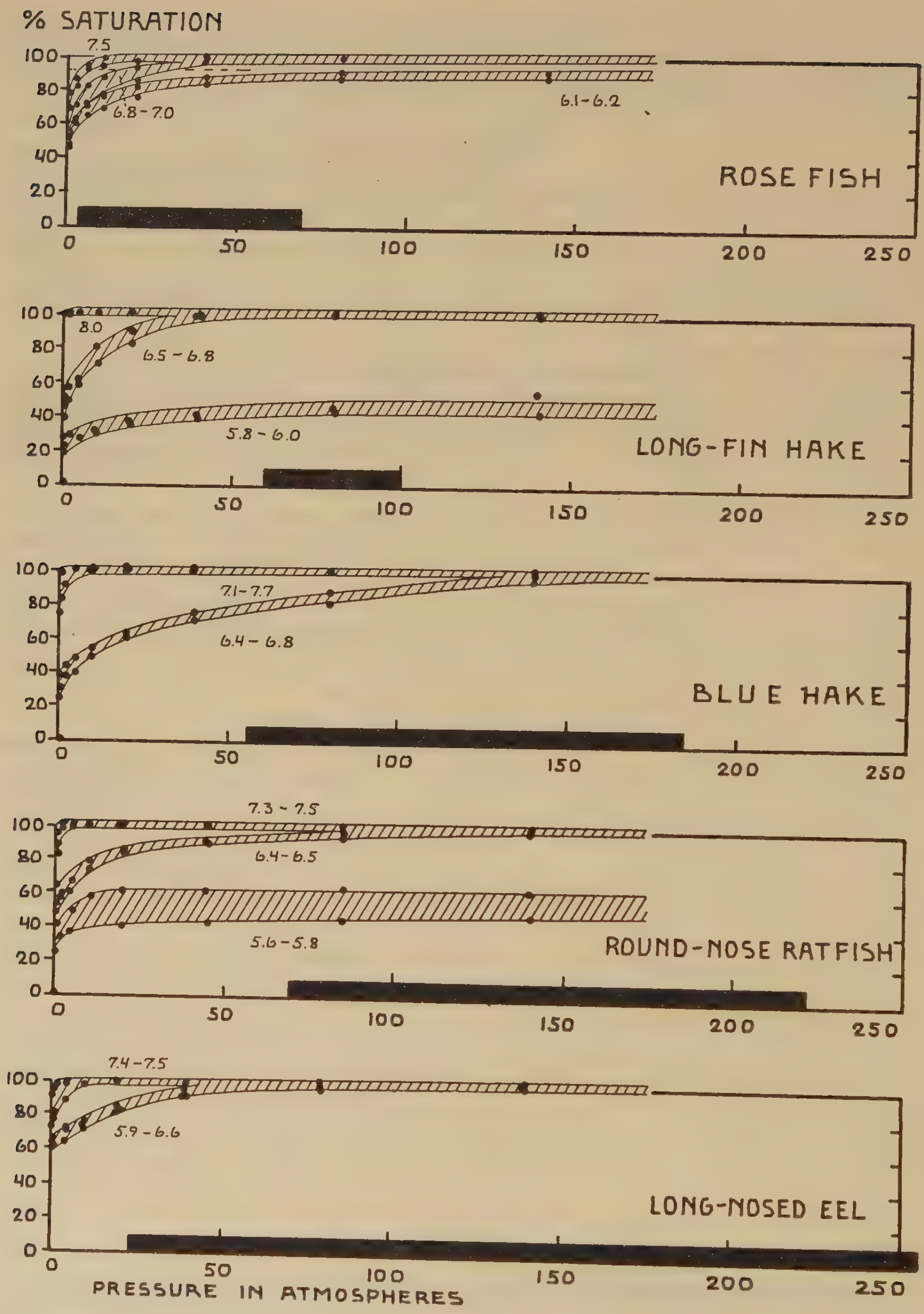

Figure 4. Oxygen saturation curves in blood of deep sea fishes at 4° C. The upper curve in each diagram represents the blood untreated, directly from the fish. In the other curves lactic acid has been added to give, after aeration, the pH stated for each curve. The solid bar on the base line is the depth range at which the fish lives. Each pH range was generally covered by two or three separate runs, using blood from different specimens. Arterial saturation would be no more than 90–95 vol. %.

bladder gas of the Bimini fishes (Table I, B), which were brought quickly to the surface. Assuming that only insignificant changes took place during the 4–7 minutes of getting the fish on deck, the tensions in the swimbladder gas were from 10–19% of one atmosphere CO_2 at the bottom. As the gas in the blown-up fish was dispersed all through its body cavity, it may well have picked up some CO_2 from the tissues.

If, as indicated by Root and Irving (1943), the CO_2 effect is simply a pH effect, then CO_2 cannot be the direct cause of the hypothetical oxygen dissociation from hemoglobin in our deep sea fishes. It was suggested by Black (1946) that HCl might be secreted rather than lactic acid. In tautog blood at pH 6.8 we found no greater Bohr effect with HCl than with lactic acid, and hence HCl does not seem to have any specific action beyond the pH effect.

In a discussion of the probable function of the *rete* it will be shown that in that connection, also, there are serious obstacles to regarding the Root effect as the basic chemical reaction responsible for the oxygen secretion in deep sea fishes (Scholander, 1954).

TABLE I

Carbon dioxide content of swimbladder gas

Species	Depth of catch (m.)	Number of specimens	% CO_2 Low—High	Mean partial pressure of CO_2 $\left(\frac{\text{atm.}}{100}\right)$
A. Tautog (*Tautoga onitis*)	0–1	2	0.49–0.99	0.7
Queen triggerfish (*Balistes vetula*)	0–2	7	0.33–0.99	0.4
Blue parrotfish (*Scarus caeruleus*)	0–2	1	1.02	1.0
Black durgon (*Melichtys piceus*)	0–2	1	1.08	1.1
Sergeant major (*Abudefduf saxatilis*)	0–1	5	0.29–0.48	0.4
B. Black grouper	320–400	6	0.17–0.40	10
Alphestes	408	1	0.47	19
Wreckfish	640	1	0.22	14

Mean value for partial pressures of CO_2: Group A, 0.9% of 1 atm.; Group B, 14% of 1 atm.

We wish to express our gratitude to Dr. C. M. Breder, Jr., Chairman of the Department of Fishes, American Museum of Natural History, for arranging our stay at the Lerner Marine Laboratory. We are much indebted to Mr. Michael Lerner, who helped us with advice and generously supplied us with equipment and machinery for deep sea fishing. Mr. and Mrs. Marshall B. Bishop spared no effort in facilitating our work at the Lerner Marine Laboratory. We have benefited much from advice and stimulating discussions with Dr. A. C. Redfield of the Woods Hole Oceanographic Institution, and we are deeply grateful to Mr. W. C. Schroeder at the same institution for all possible cooperation on the deep sea cruises which he conducted off the New England coast. Mr. C. Grant and Mr. J. L. Allen gave invaluable help in the construction of the optical instrumentation, and Mr. K. Morrison and Mr. Stanley N. Eldridge in building the deck laboratory.

Mrs. Susan I. Scholander has given us much valuable assistance in the laboratory and the field and with the manuscript.

SUMMARY

1. Oxygen dissociation curves at a P_{O_2} running from 0.2 to 140 atmospheres have been obtained from eight species of deep sea fishes, at a pH varying from 8.0 to 5.7 and at a CO_2 tension from 0.03 to 10–20% of one atmosphere.

2. The Root effect in acidified blood could be demonstrated in some of these species even up to 140 atmospheres, inasmuch as part of the hemoglobin remained unsaturated. In other species full arterial saturation occurred, however, at pH 6 or lower, at oxygen tensions much lower than those existing in the swimbladder. Hence the Root effect is not the mechanism for the oxygen secretion in deep sea fishes. If oxygen is derived from oxyhemoglobin it must be unloaded by some mechanism as yet unknown.

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SECRETION OF GASES AGAINST HIGH PRESSURES IN THE SWIMBLADDER OF DEEP SEA FISHES.

II. THE RETE MIRABILE

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II. THE RETE MIRABILE[1]

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The anatomical structure in the swimbladder of physoclist fishes associated with the gas secretion is the so-called red gland. This consists of a glandular, often button-like, structure exposed to the lumen of the swimbladder. The gland is provided with blood circulation through a so-called *rete mirabile* which consists of intermingled, parallel, unbranched, afferent and efferent capillaries. In deep sea fishes these may be more than one cm. long. In the outside layers of the swimbladder these capillaries unite to form the respective arteries and veins (Fig. 1). The structure as it varies in different fishes has been described by Woodland (1911).

The essential feature from a functional standpoint seems to be that the *rete* represents a counter current exchange mechanism where the ingoing blood is brought into intimate diffusion contact with the outflowing blood (Müller, 1840; Woodland, 1911; Haldane, 1922; Hall, 1924; Jacobs, 1930; compare Scholander and van Dam, 1954). In principle the situation can be presented as in Figure 4.

It is obvious that to maintain a gradient of 100 atmospheres or more, the millimeter-thick swimbladder wall must be very impermeable to cut down diffusion losses. This seems to be accomplished by incorporating in the wall various kinds of solids (crystals and/or fibers). In the long-nosed eel the swimbladder is strikingly silvery.

At 100 atmospheres' O_2 pressure, one volume blood would dissolve four volumes oxygen. It is therefore clear that the blood flow leaving the swimbladder would cause an impossibly great loss of oxygen unless the tension in the blood were somehow reduced before it left the bladder wall.

The problem is similar to that facing a whale moving in ice water. How can it maintain body temperature, in spite of having the big flukes circulated? This is accomplished by having the fluke arteries completely surrounded by veins, so that the arterial heat is transferred to the veins and thus remains within the bulk of the body. This very general principle of heat exchange was described by Bazett *et al.* (1948) as applicable to the *venae commitantes* in man.

Let Figure 4, I represent a counter current heat exchanger where 0° water is flowing in. It is heated to 10° at the loop by some source and returns in intimate contact with the ingoing tubes. The heat exchange will then result in the establishment of a linear temperature gradient in the tubes, as pictured (Fig. 4, II). The temperature of the leaving water would depend upon the efficiency of the heat

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exchanger, and might be one degree. If the effluent water were run out separately, isolated from the influent water, the temperature would have been 10°. Hence a ten-fold saving of heat was accomplished by the counter current exchange mechanism. If the temperature of the source of heat is fixed, it should be noted that the loop could only approach this temperature, but could not reach or exceed it.

The same situation would also obtain in regard to a diffusion exchange system in which instead of temperature we deal with gas tensions in a liquid.

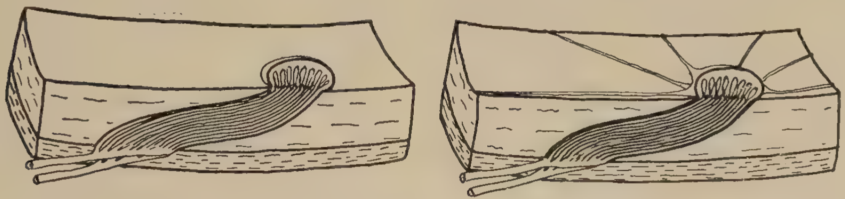

FIGURE 1. Schematic drawing of capillary *rete* and gland in relation to the swimbladder wall, which is represented with exaggerated thickness. To the left the *rete* ends in the gland (*e.g.*, in *Antimora, Coryphaenoides*) ; to the right blood vessels radiate from the gland over the surface of the swimbladder (*Sebastes, Synaphobranchus*).

MATERIAL

The deep sea material used in the present investigation was obtained from the Lerner Marine Laboratory, Bimini, and from cruises with the dragger *Cap'n Bill II* off the New England coast. (For particulars see Scholander and van Dam, 1954.)

HISTOLOGICAL STRUCTURE OF THE RETE

Sections of the *rete* from the long-nosed eel and the rosefish are given in Figure 2 (A-F). The *rete* of the rosefish is similar to that found in the common eel described by Krogh (1919). By differential injection he showed that the afferent smaller capillaries surround the larger efferent venous capillaries much in the same manner as is seen in the rosefish (D). In the ratfishes (C) these small capillaries surrounding the bigger ones are thick-walled and clearly arterial. In the long-nosed eel (A) both afferent and efferent capillaries tend to be squarish, about 13 × 13 μ. The walls between the capillaries average 1.5 μ. Most of the capillaries containing red cells are surrounded on all four sides by empty capillaries. It is believed from this that one *rete* was empty and that the *retes* are fitted together like the squares on a checkerboard.

The checkerboard arrangement is the geometrical arrangement which gives the maximal diffusion exchange between the afferent and efferent capillaries, and it is remarkable that we find it in our deepest fish. The only other solution to the topological problem of making four polygons (black or white) meet at one point in such a way that black always borders white is realized in the hexagonal star pattern found in the *rete* of the rosefish (D).

It would seem that the checkerboard pattern might have developed through a non-staggered columnar arrangement of the primary vessels (Fig. 3a), whereas the star pattern might have developed from a staggered pattern of the primary

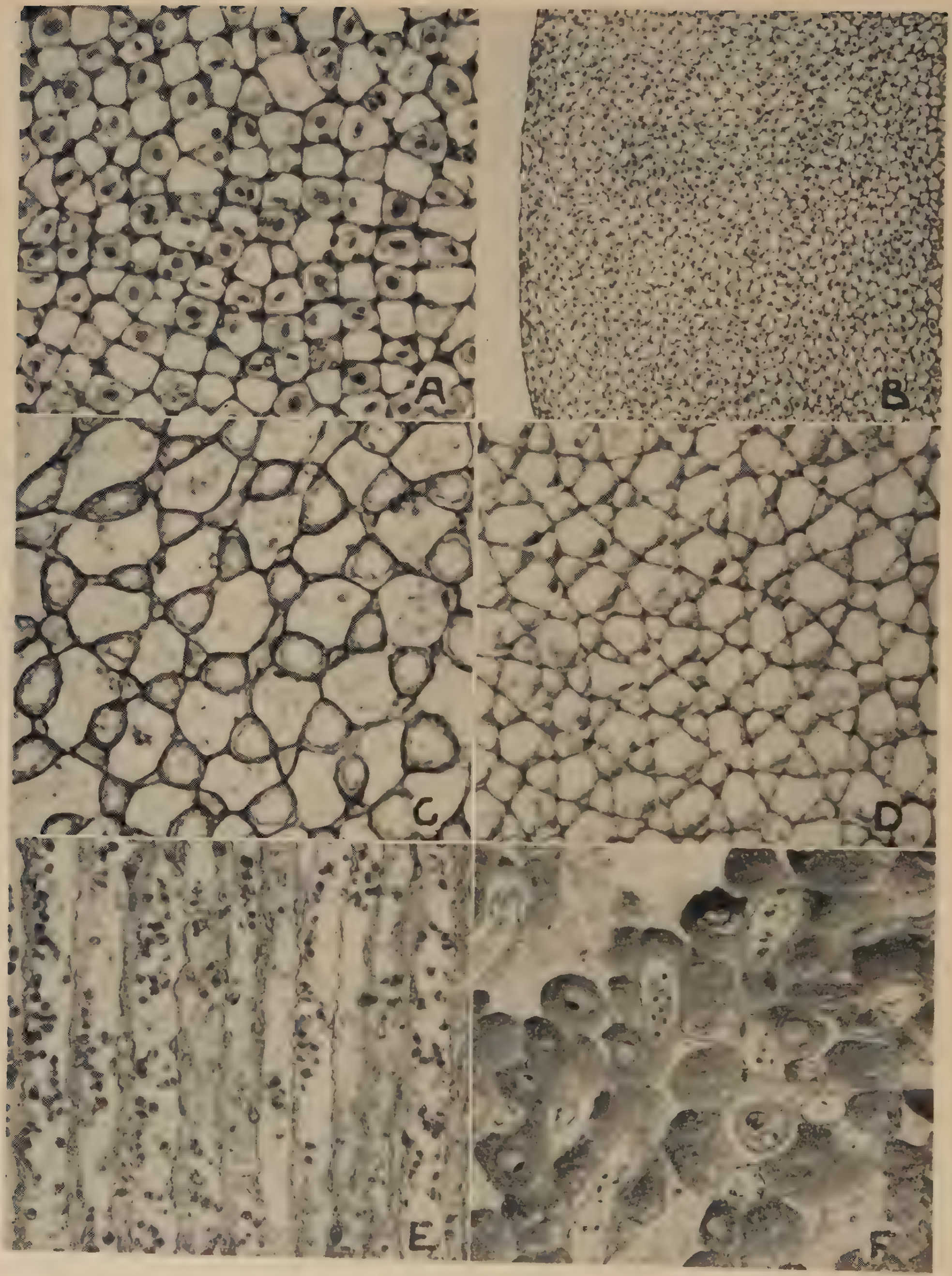

FIGURE 2. Sections through *rete* in deep sea fishes. A: *Synaphobranchus,* cross section × 300. Each polygon (square) is a single capillary. B: Same as A, × 100. C: *Coryphaenoides,* cross section × 300. D: *Sebastes,* cross section × 300. E: *Coryphaenoides,* longitudinal section × 300. Many red cells in capillaries. F: *Coryphaenoides.* Glandular epithelium from

vessels (Fig. 3b). In both cases the arterial capillaries may have developed in the interstices between the veins.

In many *retes* the loops of the glandular buttons arise from a vascular plexus located at the base of the buttons. This must naturally be so in all cases where the arterial *rete* capillaries outnumber the venous capillaries, as in the common eel, or in the rose- and ratfishes.

The length of the *rete* capillaries varies somewhat with the species, and increases generally with the depth. Measurements are given in Table I.

Figure 2F shows the surface layers of the gland "button," with capillaries surrounded by the thick glandular epithelium.

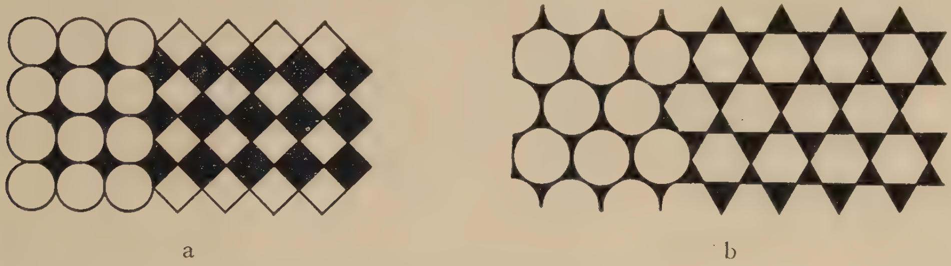

FIGURE 3. a. Possible development of the checkerboard pattern of the *rete* in *Synaphobranchus,* the primary capillaries (veins) in non-staggered rows with the arterial capillaries in the interstices. b. Possible development of *rete* in rosefish, the primary capillaries (venous) in staggered rows with the arterial capillaries in the interstices, resulting in the hexagonal star pattern.

DIFFUSION CHARACTERISTICS

From the structure and dimensions of a *rete* such as in the long-nosed eel, we may estimate what diffusion characteristics a given *rete* may have.

Let us take as unit a rete 1 cm.^{2} in cross section and 1 cm. long with capillary characteristics of the deep sea eel. The capillaries average 13 μ each side, making the circumference 52 μ. Length is 1 cm. and hence the surface area of each capillary tube is 0.0052 cm.^{2} Due to the checkered arrangement all of this surface is available for diffusion. The wall between two capillaries averages 1.5 μ. There are about 500,000 capillaries per cm.^{2} Using a diffusion constant of 150 mm.^{3}/μ/cm.^{2}/min./atm. (Krogh, 1919, p. 195), we find that the diffusion across the length of this one capillary is then 0.52 mm.^{3}/min./atm. per capillary. There are 250,000 pairs of capillaries in this *rete,* and hence the total diffusion, Q, is 130 cc./min./atm.

SYMBOLS AND BASIC EQUATIONS

It is of interest to formulate a few relations pertaining to such a counter current system in order to be able to estimate more closely what a fish *rete* might be able to do.

"button," × 225. Several capillaries are seen buried among the large glandular cells. (Staining: A, B: Gomori's chrome alum-hematoxylin and phloxine, Bouin. C: Periodic acid-Schiff, Bouin. D: Periodic acid-Schiff, 80% alcohol. E: Hematoxylin and phloxine, Bouin. F: Gomori's chrome alum-hematoxylin and eosine, Bouin.) Sections and photographs by courtesy of Dept. Anatomy, Harvard Medical School.

TABLE I

Size of fish versus length of rete mirabile

Species	Depth of catch (m.)	Length	
		Fish (cm.)	*Rete* (mm.)
Rosefish	600	46	7–9
Rosefish	600	45	8–9
Rosefish	600	32	7–8
Rosefish	600	32	7–10
Rosefish	600	32	8–10
Blue hake	900	38	7–8
Blue hake	900	37	9–10
Blue hake	900	17	9
Blue hake	900	10.5	9
Common ratfish	600	34	11–13
Common ratfish	600	28	8–9
Common ratfish	600	18	8
Common ratfish	600	16	7–8

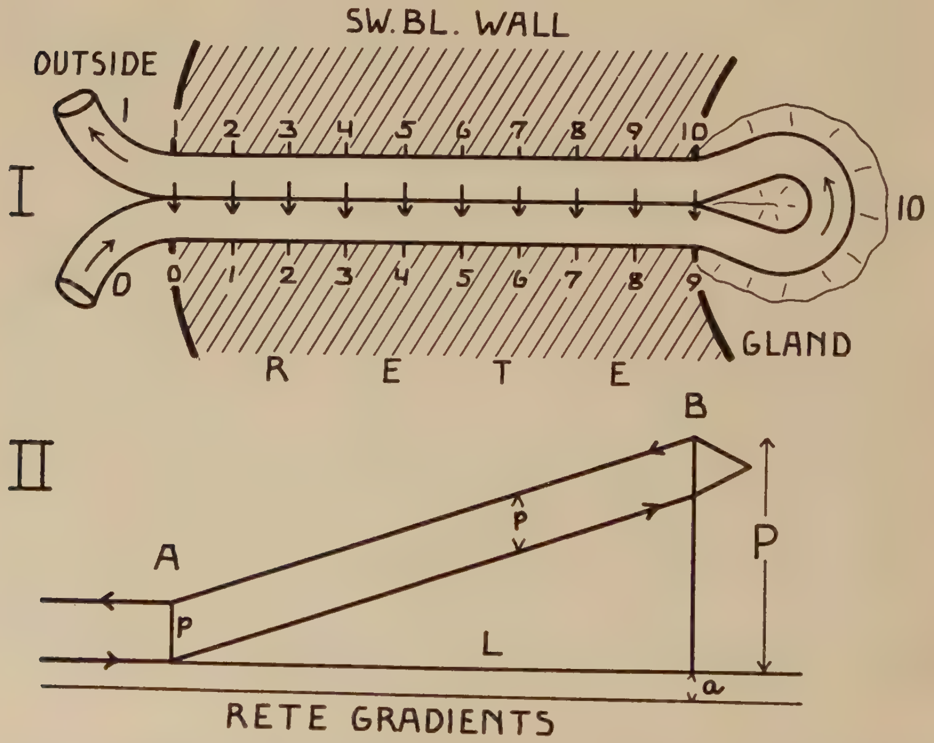

FIGURE 4. Schematic presentation of the counter current exchange principle in the swimbladder. I. Afferent and efferent capillaries. The numbers illustrate the linear gradient set up from the inside to the outside of the structure. The arrows signify the constant trans-*rete* diffusion gradient. II. Graphic representation of the gradients. L is length of the *rete;* p is trans-*rete* gradient; P is gas tension in the swimbladder; a is gas tension of inflowing blood.

Hargitay and Kuhn (1951) have developed an extensive physical treatment of this principle in relation to its probable applicability to the kidney function. Their "hairpin counter current multiplier system" is the loop of Henle. The primary concentration difference which is augmented by the system is discussed on the assumption of a semi-permeable membrane separating the afferent from the efferent flow. The difference in hydrostatic pressure due to flow presses water through the membrane and results in the primary concentration difference.

In the fish *rete* we are dealing with a different situation, inasmuch as it may be assumed that the capillaries are extremely permeable to lipid-soluble substances, especially oxygen and carbon dioxide (Pappenheimer, Renkin and Borrero, 1951), very much more so than to water. Hence it is possible to discuss the diffusion exchange in the *rete mirabile* on much simpler terms, namely, relative to what happens to gases or solutes which are simply added to the blood. The treatment is presented, realizing that it is grossly oversimplified, and at the same time it is a pleasure to credit Hargitay and Kuhn for their introduction and interpretation of the hairpin multiplier system in biology.

The following symbols will be used in the subsequent discussion:

Length of rete = L cm.
O_2 pressure in blood entering afferent *rete* = a atm.
Trans-*rete* gradient (O_2 tension gradient between afferent and efferent *rete*) = p atm.
O_2 equilibrium pressure in swimbladder = P + a atm.
O_2 pressure in blood leaving efferent *rete* (A) = p + a atm.
Blood flow = V cc./min.
Trans-*rete* diffusion = Q cc./min./atm./cm.
Solubility coefficient for oxygen in blood = α cc./cc./atm.
O_2 secreted from blood = D cc./cc.
O_2 loss by respiration and diffusion = R cc./min.

Based on the present fragmentary knowledge it seems possible that the oxygen can be secreted in two different ways: (a) molecular oxygen is directly split off from some compound in the blood, (b) oxygen in some form is transported to the glandular cells and stored there as a compound ready for intermittent use. These two possibilities will be dealt with separately.

a. *Release of oxygen directly from the blood.* It is here assumed that some constituent, at the present unidentified, is capable of dissociating off free oxygen in the blood against very high oxygen tensions. As blood cannot be stored in the gland to any significant degree, the release of oxygen stands in direct time relation to the blood flow. The fraction of the oxygen which is dissociated off and which stays dissociated off is called D and is without any connotation as to what is the nature of the responsible compound.

The diffusion characteristics of the *rete* may now be formulated in two basic equations (Fig. 4 II).

$$P\alpha V = pQ + p\alpha V \tag{1}$$

$$DV = p\alpha V + R \tag{2}$$

Equation 1 states that the amount of physically dissolved oxygen entering the effluent *rete* per minute (at B, Fig. 4) equals a fraction diffusing across the *rete* plus a fraction leaving the effluent *rete* (A). Equation 2 states that the amount of bound oxygen to be secreted, which enters at A, equals the amount of physically dissolved oxygen leaving at A plus an amount of oxygen lost from the swimbladder by other avenues (respiration, diffusion loss, etc.).

(i) *Quantitative evaluation of the rete function.* The oxygen secretion will first be dealt with without considering the term R. In equation 1 the term $p\alpha V$ is negligibly small compared to $P\alpha V$ and can be omitted. We then get the following relation:

$$\left.\begin{aligned} P\alpha V &= pQ \\ DV &= p\alpha V \end{aligned}\right\} \qquad (3)$$

and therefore

$$P = \frac{DQ}{\alpha^2 V} \qquad (4)$$

The equilibrium pressure P is consequently inversely proportional to the blood flow and directly proportional to the amount (D) of dissociated oxygen per cc. blood. P is also proportional to Q and hence to the length of the *rete.* This is borne out by the observation that for a given depth and for a given species both small and large individuals had the same length of *rete,* although the cross sections varied markedly with the size (Table I). One might make an analogy between length of *rete* and voltage, between cross section of *rete* and current (amps.).

We shall consider the *rete* equations in relation to a hypothetical but plausible deep sea fish with the following constants:

Weight	1000 g.
Swimbladder volume	50 cc.
Oxygen consumption, 8° C.	1 cc./min.
Respiratory need of swimbladder and other losses = R	0.01 cc./min.
Oxygen secreted from blood = D	0.05 cc./cc.
Oxygen solubility coefficient = α, 8° C.	0.04 cc./cc.
Trans-*rete* diffusion = Q	130 cc./min./atm.

Q varies greatly from species to species and can be given great latitude.

Let us assume a blood flow (V) through the *rete* capillaries of 1 cc. per minute and that 0.05 cc. O_2 per cc. blood (= D) is dissociated off by action of the gland. The oxygen secretion would then amount to only 50 $mm.^3$/min. or 5% of the total oxygen consumption. According to equation 4 the equilibrium pressure would then be no less than 4060 atmospheres. Obviously, therefore, if there are no losses and if the dissociation is not pressure-sensitive, the potential pressures are enormous, and would increase with lowering of the blood flow.

It is necessary to introduce a term (R) expressing the loss of oxygen by such factors as the respiratory need of the gland and the lining of the swimbladder, diffusion loss, and oxygen used for compression work.

The equations would then be:

$$\left.\begin{aligned} P &= p\frac{Q}{\alpha V} \\ DV &= p\alpha V + R \end{aligned}\right\}$$

or

$$P = \frac{(DV - R)Q}{\alpha^2 V^2} \qquad (5)$$

It is expedient at this point to consider what rates of oxygen deposition might be pertinent.

Bohr (1905) found that cod could fill its swimbladder with oxygen in about one day. Akita (1936) found the same rate for *Monacanthus.* Copeland (1952) found that *Fundulus* would need about two days, if it were able to maintain full rate for so long. If the cod and *Monacanthus* were to fill their bladders at 100 atmospheres' pressure it would take 100 days to do it. Such a drastic thing is hardly relevant for a deep sea fish. It may, however, have to compensate for a buoyancy change of, let us say, 10%, by moving from 900 meters' depth down to 1000 meters. This would require 10 days of secretion. The quantitative development of the *rete* varies greatly from species to species. Suppose that our fish can do twice as well as the cod. It would then need five days to accomplish the 10% buoyancy change and would secrete at a rate of 100 cc. oxygen of one atmosphere a day, or approximately 70 $mm.^3$/min. This would represent 7% of the total metabolic rate of the fish. Let us assume that the respiratory and diffusion loss (R) adds to it 10 $mm.^3$/min.[2] This would then give a total release of 80 $mm.^3$/min., which would require that 1.6 cc. blood per minute enter the *rete.* The potential pressure developed using these figures in equation 5 would come out as 2220 atmospheres.

When the necessary amount of gas has been deposited to accomplish the buoyancy change the fish must shut down the deposition to a simple maintenance level. This may very possibly go via a reduction of R, which may drop to, let us say, 5 $mm.^3$/min. This, according to equation 5, would make the blood flow (V) very slightly more than 0.1 cc./min., *i.e.,* 16 times less than at full secretion rate. During activity the blood vessels of the gland dilate markedly (Hall, 1924; Fänge, 1953). A less economical way of maintaining constant swimbladder volume at 100 atmospheres (or of reducing the volume) would be to draw some blood off through the non-*rete* system, like the capillaries of the "oval." Then 67 $mm.^3$/min. of O_2 would have to be run off from the swimbladder, which would require that 4 $mm.^3$ blood per minute be bled through the oval.

(ii) *Amount of oxygen secreted per cc. blood at steady state.* By considering the maximal rate at which oxygen can be deposited in the swimbladder one may calculate D, *i.e.,* the amount of dissociable oxygen carried in by the blood.

If, again, 80 $mm.^3$/min. is taken as the maximum rate of secretion and if the blood flow (V) through the *rete* is 2 cc./mm., the blood would have to unload 40 mm.^{3} oxygen per cc. blood, or more or less what the hemoglobin could do if dissociated.

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[2] The work of compressing one mol gas from 0.2 to 100 atmospheres at 8° is equal to 1.99 × T × 2.3 log (P_1/P_2) Cals. = 3.5 Cals. The caloric equivalent of one liter O_2 equals 4.8 Cal. or 104 Cal. per mol. Hence for each part of oxygen secreted into the swimbladder a minimum of 3% goes to the work of compression, or 2.1 $mm.^3$ out of the above 10 $mm.^3$ which constitute R.

The amount of physically dissolved oxygen in the blood is no more than 0.04 × 0.2 = 0.008 vol. % and therefore cannot be the source of a steady-state secretion, even if the solubility coefficient in the effluent blood were drastically lowered by some unknown process. The tension difference (p) between affluent and effluent blood could only be a few millimeters Hg.

b. *Secretion of oxygen from the gland cells.* Considering that we have failed to identify hemoglobin or any other compound in the blood as the direct source for the secreted oxygen, we must consider the possibility of a cellular secretion, where the oxygen is ultimately transported to the glandular cells via some compound in the blood. This compound, or a derivative thereof, might be stored in the epithelial cells for intermittent use. Non-steady-state events are conspicuously associated with the secretion. Glycogen is thus stored in large quantities by the gland cells if secretion is inhibited. When the gland is secreting, the glycogen is being used, and secretion cannot go on when the store of glycogen is depleted (Copeland, 1952; Fänge, 1953). If a breakdown of a stored compound is what determines the maximal rate of oxygen secretion, then the amount (D) of oxygen transported to the gland per cc. blood can be much smaller than would be necessary if the oxygen is released directly from the blood. From the information available it is impossible to decide between cellular secretion of oxygen and the release of molecular oxygen directly from the blood.

Conclusions. The discussion of the *rete* may be summarized in the following statements. The structure of the *rete* is such as to provide for an extremely efficient counter current diffusion exchange mechanism between inflowing and outflowing blood. This makes possible a steep tension gradient within the *rete* so that tension loss through the circulation becomes very low. Quantitative considerations of the diffusion efficiency of the *rete* make it clear that the limiting equilibrium pressure theoretically could reach tremendous values, provided the dissociation pressure of the underlying chemical or physical reaction is even higher. If oxygen cannot be chemically stored in the gland it must enter through the blood concomitantly with the secretion. This would require an amount of oxygen per cc. blood larger than that physically dissolved in the arterial blood. The nature of the responsible compound is not known.

THE ROLE OF LACTIC ACID AND CO_2

We have seen that thanks to the multiplication principle of the *rete,* small primary concentration effects can build up to considerable pressures, limited ultimately by the pressure characteristics of the primary chemical or physical dissociation. It was shown that the Root effect or Bohr effect at pH 6 was nullified already at 50 atmospheres in some fishes which live and secrete oxygen at much greater depths, and therefore it could not be the primary pressure reaction. Whether stronger lactic acid and lower pH could do it we do not know. It seems difficult *in vitro* to go much further without irreversible damage to the blood (Scholander and van Dam, 1954).

As regards CO_2 it was likewise shown that in some fishes 5 and 10% CO_2 would be inadequate to dissociate off oxygen at the required pressures. The question that arises is: Could the CO_2 tension be higher than this, and if so what would be the pressure characteristics of the Bohr or Root effect?

The CO_2 content of the aerated blood of several deep sea species is given in Table II. If a small amount of lactic acid were added to the blood by the gland the CO_2 pressure would build up in the *rete* and the swimbladder, and the approximate tension gradients can be calculated, inasmuch as the diffusion constant can be taken as about 25 times that of oxygen (Krogh, 1919), and the solubility coefficient is about 1.0, or again 25 times that of oxygen. This would make Q of equation 1 for $CO_2 = 25 \times 130 = 3250$ cc./min./atm.

If the CO_2 effect were responsible for the oxygen secretion in the wreckfish we would expect to find in the swimbladder at all times of steady-state a CO_2 tension higher than 10% of an atmosphere. A wreckfish caught at 640 meters had 0.22% CO_2 or 14% of an atmosphere. Six black groupers had from 6.6—13% of an atmosphere CO_2. In contrast to this 27 specimens of surface fishes, comprising 6 species, had a CO_2 tension averaging only 0.7%. It has been shown by Jacobs (1934) and von Ledebur (1937) in 10 species of physoclist fishes, which were induced to secretion by puncture, that on the average the CO_2 tension in the swimbladder rose by only 1.4—3.1% while the O_2 rose to 80–90%. In some of the species the CO_2 did not rise at all. A *Serranus cabrilla* with the oval obliterated accumulated no more than 3% CO_2 during the process of secretion. The relatively high CO_2 tensions in deep sea fishes may hence very likely be artifacts, as CO_2 diffuses so fast. If, nevertheless, we assume that our deep sea fish were to require as much as 0.5 atm. CO_2 in the swimbladder [3] to dissociate off the oxygen, and if we assume this Root effect to be reversible when the CO_2 pressure decreases, then we can estimate the rate at which such deposition could take place.

TABLE II

*Carbon dioxide content of blood**

Species	Depth of catch (m.)	Number of specimens	CO_2 (vol. %)	
			Range	Mean
A. Undiluted whole blood, aerated at 10° C.				
Black grouper	333–375	4	4.8–6.3	5.5
Alphestes	410	1	—	7.0
Wreckfish	640	2	6.8–8.0	7.4
B. Whole blood plus lactic acid 0.17 *M* (10:1), aerated at 10° C.				
Black grouper	333–375	2	1.4–1.5	1.45
Alphestes	410	1		1.9

* Method of Scholander, Flemister, and Irving (1947), modified.

If $P = 0.5$ atm., $Q = 3250$ cc./min., $\alpha\ CO_2$ is 1.0, and at a high rate of secretion $V = 1$ cc./min., then according to equation 3

$$p = 0.12 \text{ mm. Hg}$$

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[3] Tautog blood begins to hemolyze at one atmosphere CO_2.

In other words the P_{CO_2} of the "venous" blood leaving the *rete* would be only 0.12 mm. Hg higher than that of the "arterial" blood entering the *rete*. Now the oxygen *tension* of the leaving blood is always slightly higher than the tension of the entering blood. The leaving hemoglobin would hence be nearly, if not completely, arterialized. If under these circumstances any oxygen at all were deposited it would be at an infinitesimally small rate.

If the leaving CO_2 tension were to be high enough to effect a half-saturation of the hemoglobin (which is necessary for the secretion rate), one would expect at least around 10 mm. Hg CO_2 tension in the leaving blood. This would, however, require some 43 atmospheres' CO_2 tension in the swimbladder, which of course is absurd.

We see therefore that unless CO_2 at tensions higher than we tested produces some *irreversible* oxygen-splitting from the hemoglobin, we cannot accept the CO_2 effect as producing the oxygen secretion.

Koch (1934) considered that if the elevated CO_2 tension passed onto the arterial side of the *rete,* the O_2 would increase there and O_2 would diffuse across to the venous side, which would seem like a short circuit with regard to the O_2. In order to avoid this he thought that buffer might diffuse across from the arterial side to the venous, due to hydrostatic forces. If this were to happen it would at best mean a lower P (CO_2) on the venous side, hence an even earlier recombination of oxygen with the hemoglobin before the blood left the *rete,* and hence no secretion.

According to either of the two theories (CO_2 and lactic acid) the oxygen is liberated directly from the blood and hence *in* the *rete*. This obviously wastes part of the *rete* as a diffusion barrier, and the oxygen must also diffuse from the *rete* into the swimbladder. Here we encounter another seemingly backwards situation, inasmuch as in many fishes the capillary loops in the gland are covered with a deep layer of epithelial cells (Fig. 2F), which must hinder very substantially the gas diffusion into the swimbladder. The loops are also usually very much fewer than the *rete* capillaries. In order to get an efficient gas exchange we would expect rather a great many almost naked capillaries, such as in the lungs.

The anatomical arrangement seems to fit a cellular gas secretion much better. This would leave the whole *rete* as a simple counter current diffusion barrier against oxygen loss, and the secreting cells covering the capillary loops would aid the *rete* as a diffusion barrier, rather than counteract it.

There are grave difficulties in seeing the Bohr or Root effects as the cause of the secretion, and at the present time it seems indicated that many observed events associated with the secretion of oxygen, such as the occasional large rise in CO_2 (Jacobs, 1930; von Ledebur, 1937; Rostorfer, 1942), the acid formation (Hall, 1924), the glycogen disappearance (Copeland, 1952; Fänge, 1953), carbonic anhydrase activity (Leiner, 1938, 1940; Copeland, 1952; Fänge, 1953), potential glycolytic activity, lactic acid formation (Strittmatter, Ball and Cooper, 1952; Fänge, 1953) must be fitted into the secretion picture in some other way.

If dissociation of oxyhemoglobin still is to be considered as the direct cause of the pressure build-up, it must be brought about by a diffusible x-substance (from the gland cells), which would dissociate off oxygen against much higher pressure than does lactic acid. This x-substance would either have to leave with the blood and must then be quite indiffusible through the *rete* capillaries, in contrast to the gland capillaries, or if easily diffusible it would have to effect an irreversible reaction, such as methemoglobin formation, to be repaired outside the gland. Such a substance and such diffusion conditions are purely hypothetical, although perhaps possible.

There are at the present time unresolved obstacles in regarding the Root or Bohr effect as the secretion mechanism. It has not been proved that hemoglobin is involved, and it would be premature to disregard the possibility of a cellular oxygen secretion.

Conclusions. In several deep sea fishes the blood acidified with lactic acid to pH 6 or lower arterializes fully at a much lower oxygen pressure than that existing in the swimbladder. Hence lactic acid via the Root effect cannot be the cause of oxygen secretion. If the CO_2 effect were to be the cause of the secretion, CO_2 would have to leave the gland at a pressure of at least 5–10 mm. Hg. This would require a CO_2 pressure in the swimbladder of 20–40 atmospheres, which is out of the question. If hemoglobin is directly involved in the oxygen secretion the mechanism by which it is dissociated is unknown. One is led to consider seriously the possibility of a cellular oxygen secretion.

TABLE III

Nitrogen content of the swimbladder gas in deep sea fishes

Species	Depth of catch (m.)	Number of specimens	% N_2	Mean partial pressure of N_2 (atm.)
Black grouper	320–400	6	12.5–16.8	5.4
Alphestes	410	1	18.5	7.6
Wreckfish	640	1	11.0	7.0
Rosefish	660	2	20.0	13.2
Long-finned hake	1300	5	3.0–3.7	4.4
Blue Hake	1240	4	6.0–7.6	8.0
Round-nosed ratfish	1100	3	9.4–10.0	10.8
	1200–1240	3	8.4–10.3	11.6
Common ratfish (*Macrourus bairdii*)	1240	4	7.2–7.8	9.3
Long-nosed eel	1200	1	7.6	9.1

SECRETION OF INERT GASES

It has been shown that the nitrogen tension found in the swimbladder of marine fishes is practically always higher than in the sea water. In each species the nitrogen is deposited as a relatively constant proportion of the oxygen, but the fraction varies from species to species. It usually lies between 2 and 15%. In deep sea fishes the N_2 tension can therefore reach as much as 15–20 atmospheres. New data from greater depths confirm these conclusions, Table III and Figure 5. It does not seem possible to explain the high nitrogen as an artifact (Scholander and van Dam, 1953).

The whitefish (Hüfner, 1892) and several more species of freshwater physo-

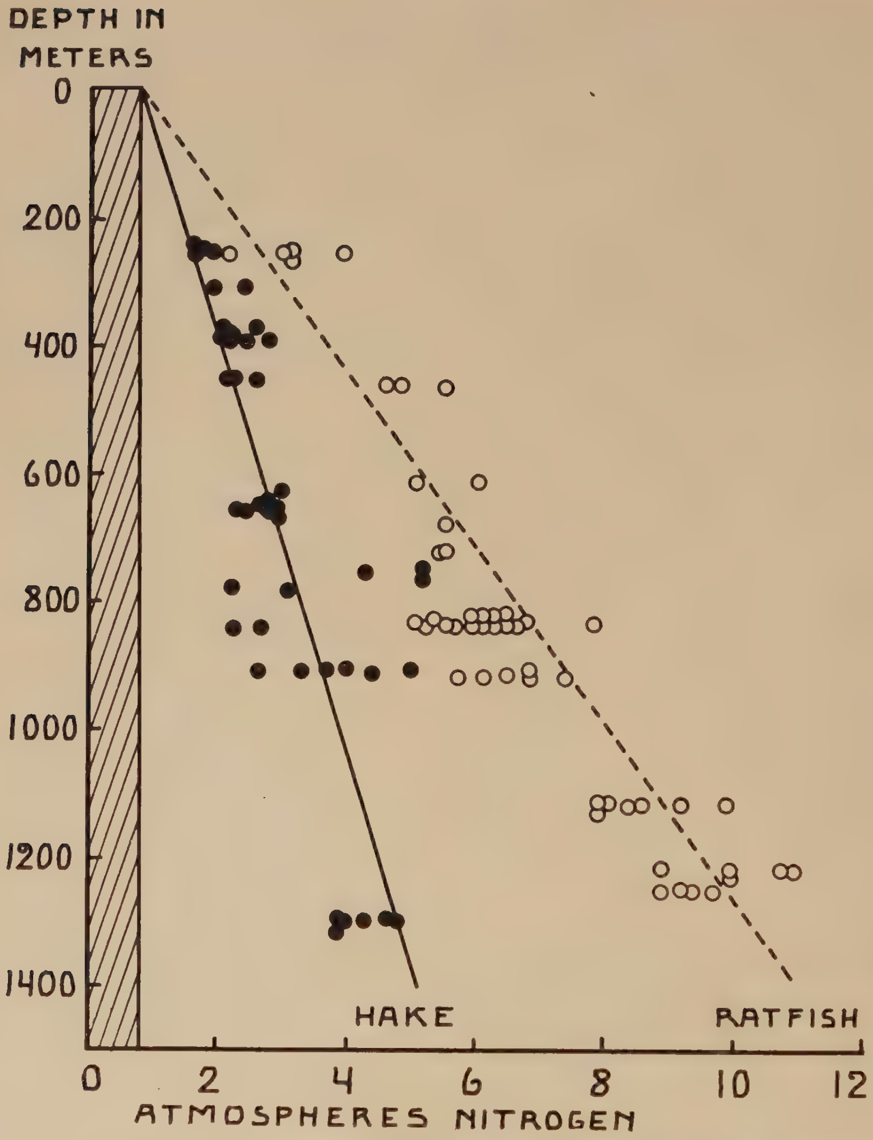

FIGURE 5. Relation of nitrogen tension in swimbladder to depth for the long-finned hake (*Urophycis chesteri*) and common ratfish (*Macrourus bairdii*).

stomes (Saunders, 1953) are able to deposit "pure" nitrogen against some 6–8 atm. pressure.

The argon-nitrogen ratio in the swimbladder. An important clue as to how basically nitrogen enters the swimbladder can be obtained by comparing the argon-nitrogen ratio in the swimbladder gas to the ratio in the air, as pointed out by Koch (1934). He considered, and rightly so, that the fact that the A/N_2 ratio found by

Schloesing and Richard (1896) was near the atmospheric ratio indicated that the nitrogen could not have been chemically secreted.

Some of our deep sea samples have been analyzed for argon. This was made possible through the courtesy of Dr. A. O. C. Nier and of Mr. Bailey Donnally, who kindly made the analyses for us on the mass spectrometer. The results will be seen in Table IV and are in favor of a physical deposition of nitrogen. If nitrogen were secreted chemically, the argon/N_2 ratio would be decreased in the given fishes between 6 and 20 times, *i.e.*, it would have been found to be between 0.2 and 0.06, instead of 1.18. Although there are substantial deviations from the air ratio they are certainly not of the order which would suggest nitrogen secretion by chemical means. Considering the fact that the argon may be expected to have twice the diffusion coefficient of nitrogen, one would expect the argon fraction to tend to be low rather than high (Scholander and van Dam, 1953).

TABLE IV

Argon-nitrogen ratio in the swimbladder gas of deep sea fishes

Species	Depth of catch (atm.)	% (N_2 + A)	N_2 + A atm.	$\frac{100A}{N_2}$
Air	1	80	0.8	1.18
Blue hake		6.2		1.16
Blue hake		6.0		1.22
Common ratfish	80	7.2	5.8	1.00
Common ratfish	80	7.6	6.1	1.61
Common ratfish	80	7.4	5.9	1.08
Rosefish	50	20.0	10.0	0.94
Rosefish	50	20.0	10.0	0.87
Long-nosed eel*	167			1.94
Moray eel*	9			1.85
Air*	1			1.18

* Schloesing and Richard, 1896. Long-nosed eel, *Synaphobranchus pinnatus*; Moray eel, *Muraena helena*.

There are unfortunately no data available on the argon/N_2 ratio in the whitefish, nor on the presence of organic gases, which would appear as nitrogen.

THEORIES FOR SECRETION OF INERT GASES

Two theories have been offered to explain the high nitrogen tensions.

a. *The bubble theory.* Powers *et al.* (1932) assumed that the Root effect would result in the formation of bubbles and that these when entering the swimbladder would transport nitrogen in from the surroundings. If the Root effect were responsible, the highest possible local pressure increase would be in the blood, and the bubbles would form there, and as Koch (1934) pointed out, it is hard to see how they would get out of the blood. Haldane (1922) pointed out that "bends" in human divers occur only if the pressure is diminished by more than 50% at a time. The highest increase in the plasma which dissociation of 9 vol. % oxygen could give is 3 atmospheres. Operating with blood equilibrated at 100 atmospheres' oxygen pressure in our cuvette, bubbles never formed at sudden drops of pressure, even ten times 3 atmospheres. Hence in deep sea fishes gas bubbles cannot very well form in the capillaries of the gland or of the *rete*. Experimentally, gas bubbles have not been observed to form within living cells, even after decompression from very high gas pressures (Harvey *et al.*, 1944). In shallow fishes, however, gas bubbles were seen to form in the mucus covering the gland when the gland was stimulated to activity (Fänge, 1953).

b. *Secretion by change in the solubility coefficient.* The second theory, proposed by Koch (1934), seems to offer a possible mechanism for the increase in nitrogen and inert gases. He considered the possibility that by some means the blood in the swimbladder vessels would have a lower solubility coefficient for gases than it does outside the swimbladder. This could come about by an increase in the temperature of the active gland, or by added solutes.

Any metabolic heat gradient would certainly be very small, as the swimbladder wall has no aspect of being a thermal insulator. Due to the extraordinry exchange capacity of the *rete* there would be, if any, only an infinitesimal difference in the temperature of blood entering and leaving the *rete*. Hence they would have the same nitrogen capacity and N_2 deposition could then not occur (equation 6).

If the solubility were depressed by the addition of some solute entering the blood from the gland, the nitrogen tension would slightly increase on the venous side. If this situation persisted so that the blood would leave the *rete* with a decreased solubility coefficient the following relation would obtain, using the symbols given above and essentially equations 1 and 2:

$$\left.\begin{aligned} P\alpha_2 V &= pQ \\ a\alpha_1 V &= (a + p)\alpha_2 V \end{aligned}\right\} \qquad (6)$$

$$P = \frac{a(\alpha_1 - \alpha_2)Q}{\alpha_2{}^2 V} \qquad (7)$$

The numerical values for the constants are: $a = 0.8$ atm.; $\alpha_1 = 0.0202$ cc./cc./atm.; $\alpha = 0.0200$ cc./cc./atm.; $V = 1$ cc./min. Q is directly proportional to the diffusion constant which for N_2 is about half that of oxygen. Q is therefore for nitrogen 65 cc./cm./cm.^{2}/min./atm.

If we have a 1% decrease in solubility at the exit of the *rete* the equilibrium pressure P would be 26 atmospheres. Theoretically, therefore, one could get enough pressure built up. It is obvious that the rate of N_2 deposition by this means would be exceedingly slow, since each cubic centimeter of blood would only transport in 0.16 mm.^{3} N_2/min.

A striking thing about the nitrogen tension in the swimbladders of our marine fishes is that in most of them it increases linearly with the depth, as if the nitrogen were produced as a constant percentage of the oxygen secretion. This observed phenomenon ($P_{N_2}/P_{O_2} = 2$–15%, and independent of pressure) could only be derived from the equations 5 and 7 if R were either proportional to the pressure or if it were constant, neither of which assumption seems likely to be true. There is a further difficulty with the proposed theory where an x-substance produces the lowering of the solubility coefficient, in that if the substance were diffusible it would be likely to concentrate enormously in the inner part of the *rete*. And if it were not diffusible how would it have entered the blood stream in the first place? Another serious difficulty is that physostomes like the whitefish evidently lack a typical *rete*.

Conclusions. The nitrogen-to-argon ratio in the swimbladder of deep sea fishes was found to be approximately that of the sea water and atmosphere, confirming what was found earlier by Schloesing and Richard (1896). In these fishes, therefore, the nitrogen has not been chemically secreted.

The theory of Koch (1934) that nitrogen and argon might be secreted into the swimbladder by a decreased solubility coefficient in the effluent blood of the *rete* has been evaluated quantitatively. Although high enough equilibration pressures of nitrogen could be achieved by a small change in the solubility coefficient, the constant ratio N_2/O_2 at all depths, as actually found, cannot readily be explained by this theory. The theory may not apply to physostomes, like the whitefish, which seem to lack a typical *rete*.

During this work I have received many suggestions from stimulating discussions with Dr. A. C. Redfield and Dr. L. van Dam at the Woods Hole Oceanographic Institution. I am much obliged to Dr. A. O. C. Nier and to Mr. Bailey Donnally at the Physics Department of the University of Minnesota for mass spectrographic analyses of the argon/nitrogen ratio in the swimbladder gases. Dr. George Wislocki, Department of Anatomy, Harvard Medical School, has generously given his help and advice with regard to the histological material. This long-preserved material was most skillfully prepared by Mrs. Edith Herman and photographed by Mr. Leo Talbert of the same department. I am much indebted to Dr. C. M. Breder, Jr., of the American Museum of Natural History, for arranging our work at the Lerner Marine Laboratory, and I wish to thank Mr. Michael Lerner and the staff of the Lerner Marine Laboratory for all the help they extended to us. Mr. W. C. Schroeder of the Woods Hole Oceanographic Institution gave us the best of facilities on board the dragger *Cap'n Bill II,* and for much assistance in the laboratory and with the manuscript thanks are due to Dr. L. van Dam and Mrs. Susan I. Scholander.

SUMMARY

1. The structure and dimensions are given for the *rete mirabile*. It is interpreted as a counter current diffusion exchange mechanism between the afferent and efferent *rete*.

2. This diffusion exchange has been quantitatively evaluated for O_2, CO_2, and N_2. The arrangement makes possible the maintenance of a steep tension gradient within the *rete,* so that the oxygen loss from the leaving blood can be extremely low.

3. Quantitative evaluation of the efficiency of the *rete* diffusion makes it clear that the limiting equilibrium pressure in the swimbladder could be extremely high, and that the limiting factor lies mainly in the dissociation pressure of the chemical or physical reaction which ultimately splits off the oxygen.

4. The nature of the responsible compound and reaction is unknown. The anatomical arrangement of the glandular structure and the *rete* is suggestive of a

cellular secretion of oxygen rather than of a mechanism that splits off oxygen in the blood.

5. Data on the deposition of nitrogen against high pressures which were previously found in deep sea fish have been confirmed and extended. The argon-to-nitrogen ratio in the swimbladder gas suggests that the nitrogen has entered the swimbladder via some physical mechanism. The possibility that this is brought about by a lowering of the nitrogen solubility coefficient in the efferent *rete* is discussed.

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Convection of Heat[1].

By

R. B. Montgomery.

Summary. Several aspects of the formulation and physical meaning of heat flux by convection are discussed. Convective heat flux is uniquely determined only when the flux of each constituent substance vanishes. For uniform composition, the physically satisfactory formulation of eddy flux of heat is in terms of the velocity fluctuation about the weighted mean introduced by HESSELBERG, but in some important problems this formulation is practically the same as SWINBANK's. It is suggested that convective heat flux be interpreted to include the flux of not only enthalpy but also potential energy.

Zusammenfassung. Es werden mehrere Möglichkeiten der Formulierung und der physikalischen Interpretation des Wärmeflusses durch Konvektion diskutiert. Der konvektive Wärmefluß ist nur dann eindeutig bestimmt, wenn der Fluß der einzelnen Komponenten verschwindet. Eine physikalisch befriedigende Formulierung der Wärmescheinleitung im Falle eines homogenen Mediums läßt sich mittels Geschwindigkeitsschwankungen um die ausgeglichene Bewegung gewinnen, wie sie von HESSELBERG eingeführt wurden; doch ist diese Formulierung bei einigen wichtigen Problemen praktisch identisch mit der von SWINBANK. Es wird vorgeschlagen, unter konvektivem Wärmefluß nicht nur den Fluß von Enthalpie, sondern auch den von potentieller Energie zu verstehen.

Résumé. Cet exposé discute les divers aspects du sens physique du flux calorifique dû à la convection. Le flux convectif de chaleur n'est déterminé absolument que lorsque le flux de chaque constituant est égal à zéro. Pour une composition uniforme, la formule physiquement satisfaisante du flux calorifique dû à la turbulence est en fonction de la fluctuation de la vitesse par rapport à la moyenne pondérée introduite par HESSELBERG. Dans certains problèmes importants, cette formule est cependant pratiquement

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la même que celle de Swinbank. L'auteur propose d'interpréter le flux de chaleur convectif de manière à y inclure non seulement le flux d'enthalpie, mais aussi le flux d'énergie potentielle.

That motions of the scale shown by weather maps can advantageously be treated statistically as turbulence was first demonstrated in Albert Defant's famous paper of 1921 on the circulation of the atmosphere [*1*]. From an estimated coefficient of meridional exchange and the observed meridional gradient of mean temperature he was able to calculate the meridional heat flux by eddy convection. Recently Priestley [*7*] and White [*13*] have calculated this heat flux directly from instantaneous values of temperature and meridional component of velocity.

The present paper deals with the general concept *convection of heat*, not limited to horizontal flux. The purpose is to resolve questions that have arisen regarding the formulation and basic physical meaning of heat convection. Further evidence is found in support of the formulation of eddy convection of heat that is based on the weighted means introduced by Hesselberg [*2, 3*].

I. Convective Flux of Heat.

One can readily formulate the convection of substance, but difficulties arise if the same formulation is heedlessly applied to the convection of heat. The convective flux of a substance of density (or partial density) ϱ_1 through a surface A can be expressed in terms of v_n, the normal component of velocity relative to the surface, as

$$\int_A \varrho_1 v_n \, \delta A; \tag{1}$$

this quantity is a definite flux of mass, and no ambiguity arises. The convective flux of heat has sometimes been stated in a formally similar way in terms of the density (of the mixture) ϱ and the specific enthalpy h as

$$\int_A \varrho v_n h \, \delta A. \tag{2}$$

In general this quantity, however, is not uniquely determined, because the specific enthalpy of each substance is reckoned from an arbitrary zero point. For instance, at a given section of a current (air current, ocean current, or flow of fluid through a tube) the flux of each constituent is uniquely specified by (1), but no absolute value for the heat flux can be obtained by (2). In other words, the distributions of velocity, composition, and temperature over the section do not by themselves determine a meaningful heat flux.

The important consideration is that the quantity (2) becomes unique and generally meaningful only in the special case that the flux of each constituent vanishes,

$$\int_A \varrho_1 v_n \, \delta A = 0, \quad \int_A \varrho_2 v_n \, \delta A = 0, \ \ldots, \tag{3}$$

for then the arbitrary constant in the specific enthalpy of each substance contributes nothing to the integral (2). Such a special case occurs if the surface A encloses a system containing constant mass of each constituent. One such system is a constant-flow system. (If a system completes a cycle so that the mass of each constituent returns to the initial value, the integral of the flux (2) over the cycle is also unique and meaningful.)

To illustrate these conclusions, consider now the surface A forming a section across a channel in which the current carries a net flow of mass. Suppose that the zero point of enthalpy has been chosen for each substance involved and that the flux (2) has been calculated accordingly. The flux (2), depending as it does on the arbitrary zero points, has no significance by itself. Thus, for instance, it is meaningless to speak of the heat flux of a single ocean current. It is common in engineering, however, to calculate the flux (2), meaningless by itself, because the sum of these fluxes over all the channels forming the openings of a steady-flow system equals the convective flux of heat for the system.

II. Eddy Flux of Heat with Uniform Composition.

The formulation of eddy flux of heat is discussed in the present section for a fluid of uniform composition. The condition that

$$\int_A \varrho\, v_n\, h\, \delta A \qquad (2)$$

represent a definite flux of heat becomes simply

$$\int_A \varrho\, v_n\, \delta A = 0. \qquad (4)$$

Hesselberg [2, 3] proposed that for turbulent flow with instantaneous velocity $\boldsymbol{v}$ the useful mean velocity is the weighted mean defined as

$$\bar{\boldsymbol{v}}_\varrho = \{\varrho\, \boldsymbol{v}\}/\bar{\varrho}. \qquad (5)$$

The notation of the present paper is that a mean is represented either by a superior bar or by braces $\{\ \}$. (A weighted mean is marked with a subscript ϱ; absence of subscript indicates a simple mean.) The same weighted mean has been discussed by Montgomery [5], Van Mieghem [11, 12], and Miller [4]. Let

$$\boldsymbol{v} = \bar{\boldsymbol{v}}_\varrho + \boldsymbol{v}''. \qquad (6)$$

Multiplying by ϱ and taking means shows, in view of (5), that $\{\varrho\, \boldsymbol{v}''\} = 0$, subject to the condition that $\bar{\boldsymbol{v}}_\varrho$ is constant. (That this important condition is not necessarily fulfilled is recognized but is not discussed here.)

If the surface A moves with velocity $\bar{\boldsymbol{v}}_\varrho$, then the normal component of velocity relative to the surface is v_n'', so that the instantaneous flux of mass is

$$\int_A \varrho\, v_n''\, \delta A$$

and the mean flux of mass is

$$\int_A \{\varrho\, v_n''\}\, \delta A = 0.$$

Therefore the quantity

$$\int_A \{\varrho\, v_n''\, h\}\, \delta A \tag{7}$$

is a definite convective flux of enthalpy. It is proposed to call (7) the *eddy flux of heat* through the surface A. The unit-area eddy flux of heat in the n direction is $\{\varrho\, v_n''\, h\}$, which is a component of the vector unit-area eddy flux of heat, $\{\varrho\, \boldsymbol{v}''\, h\}$. This formulation of eddy flux of heat was presented by HESSELBERG [*3*, § 6], MONTGOMERY [*5*, *6*], and VAN MIEGHEM [*11*, § 22; *12*], each using different ways to reach the same result.

In other words, a surface moving with the mean flow $\bar{\boldsymbol{v}}_\varrho$ (i. e., an individual surface with respect to the mean flow $\bar{\boldsymbol{v}}_\varrho$) has the unique advantage that the mean flux of mass through the surface is everywhere zero, so that the mean flux of enthalpy assumes a definite value that can properly be called the eddy flux of heat. Indeed, the physical idea of an eddy flux can best be formulated as the mean flux relative to natural coordinates that everywhere move with the mean flow $\bar{\boldsymbol{v}}_\varrho$, just as true conduction (or diffusion) can best be formulated as the flux relative to natural coordinates moving with the instantaneous fluid velocity. For instance (to digress from uniform composition), the eddy diffusion of smoke from a drifting puff can advantageously be studied in terms of the flux of smoke through a closed surface surrounding the maximum concentration. If each point of the surface moves with the local mean flow $\bar{\boldsymbol{v}}_\varrho$, the enclosed total mass remains constant and the rate of decrease of enclosed smoke equals the eddy diffusion of smoke outward through the surface.

It may be noted that the present formulation of eddy flux of heat is not limited to constant pressure: the pressure may vary over the surface A and may fluctuate with time at any point of A. The validity of this statement was demonstrated [*5*] for vertical eddy flux of heat in the atmosphere[1], and general validity seems acceptable.

A different formulation of eddy flux has been advanced by SWINBANK [*9*] and PRIESTLEY and SHEPPARD [*8*, pp. 498, 503–504]. The surface they use is stationary relative to the earth's crust. They call $\varrho\, v_n\, h$ the (unit-area) flux of heat. The product of the unit-area mean flux of mass $\{\varrho\, v_n\}$ and the mean specific enthalpy $\bar{h}$ is $\{\varrho\, v_n\}\, \bar{h}$, which they call the (unit-area) mass flux of heat. Let

$$\varrho\, v_n = \{\varrho\, v_n\} + (\varrho\, v_n)'. \tag{8}$$

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[1] G. D. ROBINSON, in his "Reply" following my comments [*6*], says he believes that the restriction to negligible fluctuation of pressure is implied in my first paper [*5*]. He erroneously assumes that I imply "that p is a time mean of pressure." On the contrary, I stated explicitly [*5*, p. 267]: "The pressures in the system and its volume and shape may change."

The unit-area eddy flux of heat is then defined as $\{(\varrho\, v_{\mathrm{n}})'\, h\}$, which equals the difference $\{\varrho\, v_{\mathrm{n}}\, h\} - \{\varrho\, v_{\mathrm{n}}\}\, \bar{h}$. Both terms of this difference depend on an arbitrary constant and have no significance by themselves. The quantity $\{(\varrho\, v_{\mathrm{n}})'\, h\}$ is indeed independent of the arbitrary constant, but significance is not gained by that fact alone, for the quantity $\{x'\, h\}$ involving any variable x would be independent of the arbitrary constant in h. It is not clear to me, therefore, that $\{(\varrho\, v_{\mathrm{n}})'\, h\}$ has physical significance, either in itself or as the difference between $\{\varrho\, v_{\mathrm{n}}\, h\}$ and $\{\varrho\, v_{\mathrm{n}}\}\, \bar{h}$.

Swinbank's quantity $\{(\varrho\, v_{\mathrm{n}})'\, h\}$ and the quantity $\{\varrho\, v_{\mathrm{n}}''\, h\}$ here proposed are different, for (5, 6, 8) yield

$$\varrho\, v_{\mathrm{n}}'' - (\varrho\, v_{\mathrm{n}})' = \bar{\varrho}\, \bar{v}_{\mathrm{n}\varrho} - \varrho\, \bar{v}_{\mathrm{n}\varrho} = -\bar{v}_{\mathrm{n}\varrho}\, \varrho',$$

so that

$$\{\varrho\, v_{\mathrm{n}}''\, h\} - \{(\varrho\, v_{\mathrm{n}})'\, h\} = -\bar{v}_{\mathrm{n}\varrho}\, \{\varrho'\, h\}. \qquad (9)$$

Swinbank [*9, 10*] calculated $\{(\varrho\, v_z)'\, h\}$, v_z being the velocity component vertically upward, as part of his pioneering measurement of vertical fluxes a short distance above the ground. As $\bar{v}_{z\varrho}$ is small in Swinbank's problem, his calculated values of $\{(\varrho\, v_z)'\, h\}$ are for practical purposes equal to $\{\varrho\, v_z''\, h\}$, which is a basically sound formulation of the unit-area upward eddy flux of heat. In other words, although the theoretical validity of his formulation is questioned, there is no doubt that his formulation is fully valid for practical purposes.

Further insight into this difference can be gained by considering Swinbank's problem more fully. At a fixed point above ground he measured temperature and $\varrho\, v_z$. His purpose was to calculate the vertical eddy flux of heat, so that this flux could, for example, be compared with the radiative fluxes. He realized that at the point of measurement the mean vertical flow $\{\varrho\, v_z\}$ may differ from zero, owing either to the ground not being level and smooth or to the presence of vertical circulation, and he wanted to avoid any contribution of the mean vertical motion to the eddy flux of heat. It is helpful to focus attention on a quasi-level surface that contains the point of measurement and that at all points is tangent to the flow direction, given by the vector $\{\varrho\, \boldsymbol{v}\}$. Let n be the upward normal to the quasi-level surface; then $\{\varrho\, v_{\mathrm{n}}\} = 0$. The unit-area eddy flux of heat across the quasi-level surface (by either definition) is $\{\varrho\, v_{\mathrm{n}}\, h\}$.

The eddy flux of heat at the point has three natural components: one in the direction of n, one in the flow direction, and one in the horizontal direction normal to the flow direction. The vertical flux is the sum of the vertical components of the first two natural components of flux. As the first natural component is nearly vertical, it may be considered equal to its vertical component. Hence the unit-area vertical eddy flux of heat is the sum of $\{\varrho\, v_{\mathrm{n}}\, h\}$ and of the vertical component of the unit-area eddy flux of heat in the flow direction. A representative value of $\{\varrho\, v_{\mathrm{n}}\, h\}$ is 0.1 $\mathrm{cal\,cm^{-2}\,min^{-1}}$. The unit-area eddy flux of heat in the flow direction differs according to the two definitions, as may be seen from (9), by the amount $-\bar{v}_{\varrho}\, \{\varrho'\, h\}$, where $\bar{v}_{\varrho}$ is the magnitude of the flow velocity $\bar{\boldsymbol{v}}_\varrho = \{\varrho\, \boldsymbol{v}\}/\bar{\varrho}$. Representative values of 5 m/s for $\bar{v}_\varrho$ and 0.5 C for the temperature fluctuation give (where T is absolute temperature, c_p is isobaric specific heat, and p is pressure)

$$-\{\varrho'\, h\} = -\{\varrho'\, h'\} = -c_p\, \{\varrho'\, T'\} = (p/0.286)\, \{(T'/T)^2\} \sim 10 \text{ dyne cm}^{-2},$$

so that

$$-\bar{v}_\varrho\, \{\varrho'\, h\} = 5 \times 10^3 \text{ erg cm}^{-2}\text{ s}^{-1} = 0.007 \text{ cal cm}^{-2}\text{ min}^{-1}.$$

The vertical component of this flux difference is insignificant.

III. Eddy Flux of Heat in a Variable Mixture of Two Constituents.

Actually the composition of the atmosphere varies. At any point the specific humidity q fluctuates, and this fluctuation is accompanied by an eddy flux of aqueous vapor. The unit-area eddy flux of vapor may be defined as $\{\varrho\, \boldsymbol{v}''\, q\}$, with component $\{\varrho\, v_n''\, q\}$ in the n direction. This flux is balanced by an equal and opposite flux of dry air. The condition (3) is not fulfilled, and there is no unique and generally meaningful formulation of convective flux of heat. In special cases the heat flux can be formulated in terms of the effect on some chosen system, but there is no general formulation in terms of only the conditions at a given point. The eddy flux of heat can sometimes be formulated in a practically satisfactory way, but an arbitrary constant is always involved and must be chosen within reason. The fluxes of sensible heat and latent heat will be discussed, but they are found to be not fully separable.

A two-constituent mixture is considered, at first in general. Let the proportions by mass of constituents 1 and 2 be P_1 and $1 - P_1$. Let the specific enthalpies of the separate constituents be h_{1a} and h_{2a}, which are measured from arbitrary states 1a and 2a of zero enthalpy. If the enthalpy of the mixture equals the sum of the enthalpies of the separate constituents, the specific enthalpy of the mixture is

$$h_a = P_1\, h_{1a} + (1 - P_1)\, h_{2a}. \tag{10}$$

The unit-area eddy flux of enthalpy in the n direction is

$$\{\varrho\, v_n''\, h_a\} = \{\varrho\, v_n''\, [P_1\, h_{1a} + (1 - P_1)\, h_{2a}]\}. \tag{11}$$

If the two states of zero enthalpy are differently chosen, the specific enthalpies of the constituents being h_{1b} and h_{2b}, the unit-area eddy flux of enthalpy becomes

$$\{\varrho\, v_n''\, h_b\} = \{\varrho\, v_n''\, [P_1\, h_{1b} + (1 - P_1)\, h_{2b}]\}.$$

The difference is

$$\{\varrho\, v_n''\, h_b\} - \{\varrho\, v_n''\, h_a\} = [(h_{1b} - h_{1a}) - (h_{2b} - h_{2a})]\, \{\varrho\, v_n''\, P_1\}. \tag{12}$$

It is seen that, as the constant in brackets is arbitrary, the eddy flux of enthalpy is undetermined as long as there is an eddy flux of the separate constituents ($\{\varrho\, v_n''\, P_1\} \neq 0$).

Returning to the consideration of air, both constituents are treated as perfect gases with constant isobaric specific heats, c_{pd} for dry air and $c_{p\mathrm{w}}$ for aqueous vapor. The specific enthalpies of the separate constituents may be written

$$h_\mathrm{d} = c_{p\mathrm{d}}\,(T - T_{0\mathrm{d}}),\quad h_\mathrm{w} = c_{p\mathrm{w}}\,(T - T_{0\mathrm{w}}) + L_0, \tag{13}$$

where T is temperature (on any predetermined scale) and $T_{0\mathrm{d}}$ is the arbitrary temperature at which the enthalpy of dry air is zero. The specific enthalpy of aqueous vapor is written to include the latent heat, $T_{0\mathrm{w}}$ being the arbitrary temperature at which the enthalpy of liquid water is zero and L_0 being the latent heat of vaporization at this temperature. The specific enthalpy of the mixture is

$$h = (1 - q)\,h_\mathrm{d} + q\,h_\mathrm{w}. \tag{14}$$

The resulting unit-area eddy flux of enthalpy in the n direction is

$$\{\varrho\, v_\mathrm{n}''\, h\} = c_{p\mathrm{d}}\,\{\varrho\, v_\mathrm{n}''\,(T - T_{0\mathrm{d}})\} + \{[c_{p\mathrm{w}}\,(T - T_{0\mathrm{w}}) - \\ - c_{p\mathrm{d}}\,(T - T_{0\mathrm{d}})]\,\varrho\, v_\mathrm{n}''\, q\} + L_0\,\{\varrho\, v_\mathrm{n}''\, q\} \tag{15}$$

(which can be rearranged in a variety of ways). Of the three terms on the right, the first is independent of the constant $T_{0\mathrm{d}}$, but the other two depend on an arbitrary constant.

In trying to separate the right side of (15) into fluxes of sensible heat and latent heat, one might think that the second term belongs entirely to the flux of sensible heat. The second and third terms, however, both depend on the arbitrary constant $T_{0\mathrm{w}}$ and therefore are not fully separable in physical interpretation. If the arbitrary constants $T_{0\mathrm{d}}$ and $T_{0\mathrm{w}}$ are sufficiently close to the average temperature, the second term is small and may be neglected in practice. The term is not small, however, if $T_{0\mathrm{d}}$ and $T_{0\mathrm{w}}$ are given extreme values like absolute zero.

If the second term on the right of (15) can be neglected, the unit-area eddy flux of sensible heat is given by the first term, $c_{p\mathrm{d}}\,\{\varrho\, v_\mathrm{n}''\,(T - T_{0\mathrm{d}})\}$. The unit-area eddy flux of latent heat is given by the last term, $L_0\,\{\varrho\, v_\mathrm{n}''\, q\}$, which depends on $T_{0\mathrm{w}}$. It is advantageous to choose $T_{0\mathrm{w}}$ to be close to the temperature of the water surfaces where evaporation and condensation occur [*5*, p. 270; *6*].

IV. Nonuniform Geopotential.

It has been tacitly assumed in the preceding sections that geopotential is essentially uniform over the surface through which the flux is computed. If geopotential is not uniform, the convective heat flux may well be identified not with the flux of enthalpy alone as in (2) but with the quantity

$$\int_A \varrho\, v_\mathrm{n}\,(h + \Phi)\,\delta A, \tag{16}$$

where Φ is geopotential.

Let A be a vertical surface extending around the earth at constant latitude and from the bottom of the ocean to the top of the atmosphere, and let v_n be the horizontal poleward component of velocity. Suppose there is a direct thermal circulation: equatorward flow at low levels and poleward flow aloft, the air in the poleward flow being potentially warmer but actually colder. The flux of mass, (1), is close to zero, at least if a mean is taken over a sufficient time. The poleward flux of enthalpy, (2), is negative. The poleward flux of $h + \Phi$, (16), is positive and represents the poleward flux of energy (kinetic energy being neglected).

It is merely a matter of definition whether (2) or (16) is called the heat flux. If one wants to think of a direct thermal circulation as carrying heat from the warm source to the cold source, he must choose (16).

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NORTHERLY OCCURRENCES OF WARM-WATER FISHES IN THE WESTERN ATLANTIC.—In the summer and fall of 1953, I was able to record several northerly occurrences of warm-water fishes of the families Scombridae, Carangidae and Coryphaenidae. These include some individuals taken from research vessels of the Woods Hole Oceanographic Institution in offshore waters, and others caught in Mr. Norman Benson's trap at Quissett, Massachusetts, in Buzzards Bay.

Some of the captures appear to constitute new northern records. Others are of species which have previously been listed from these latitudes but whose occurrences there are not often described in the literature. Abundance or scarcity of the respective species was checked in Bigelow and Schroeder (1953, Fish. Bull. U.S.F.W.S., 53 (74): 1–577) for the Gulf of Maine, and in Nichols and Breder (1934, Zoologica, 9 (1): 1–192) for New York and southern New England, and other regional works, as well as COPEIA and the *Zoological Record*.

Neothunnus albacares (Bonnaterre).—Two yellowfin tuna, each 117 cm. long, were taken by trolling from the ATLANTIS in waters southeast of New York. One was caught on October 24 about 100 miles from that port, where the Hudson Canyon crosses the 100-fathom curve (39°22′N, 72°22′W), and the other was taken on November 11 about 110 miles further to the southeastward (38°18′N, 70°29′W), about 183 miles south of Martha's Vineyard. Catches of this species in northern waters by sport fishermen have been reported occasionally in the nonscientific press, but in such cases the identification is often open to question. The species is not recorded in scientific literature from the Gulf of Maine, or from New York and southern New England. Nichols and LaMonte (1941, Ichthyol. Contrib. Internat. Game Fish Assoc., 1 (3): 30) listed a specimen (as *Neothunnus albacora*) taken off Ocean City, Maryland, (38°23′N). These captures, therefore, occurred at or near the probable northern limit of the range of the species, although some individuals may have been taken off northern New Jersey or Long Island.

Scomberomorus cavalla (Cuvier).—Thirteen king mackerel averaging 70 cm. in length were taken in the trap at Quissett between September 28 and October 9. This species was not known from the Gulf of Maine until as recently as August, 1949, when one was taken at North Truro, Cape Cod. This is the most northerly record of its occurrence. It was listed as formerly abundant, now rare, off New York and southern New England.

Seriola falcata Cuvier and Valenciennes.—A falcate amberjack 34 cm. long was taken from a school of about a dozen individuals of similar size which approached the ATLANTIS when she was hove to on November 1 (39°09′N, 62°05′W), about 610 miles east of Cape May. While it is not unusual to find juvenile carangids drifting with weeds in the offshore waters, the larger individuals are seldom recorded so far from land. Two specimens, 8 and 27 cm. long, respectively, were taken near the surface along with two *Caranx ruber* and over 200 *C. crysos* in a 2-meter ring net from the BEAR on September 10 (39°13′N, 71°13′W), about 145 miles east of Atlantic City. As I have found no mention of the occurrence of this species north of Bermuda and Cape Hatteras, these captures appear to constitute a new northern record.

Caranx crysos (Mitchill).—Ten blue runners averaging 40 cm. in length were taken close to the surface with hook and line from the CAPT. BILL II on July 29 (40°04′N, 70°34′W), 77 miles south of Martha's Vineyard. The offshore capture of large blue runners is unusual, as the adults of this species are regarded as inshore fishes. About 40 individuals from 6 to 15 cm. long were caught at the surface by net from the BEAR on August 26 (39°29′N, 70°40′W), 112 miles south of Martha's Vineyard. Over 200 *crysos* of this same size range were taken from this vessel in the same general area on September 10, along with the two *C. ruber* and two *Seriola falcata*, as mentioned above. The capture of so many small individuals in the offshore waters is interesting in view of the nursery area for the species defined by Nichols (1939, Bull. Bingham Oceanogr. Coll., 7 (2): 1–9) as extending from 37°12′ to 32°59′N and from 67°39′ to 69°46′W in late August. This area is not far south and east of the locations where so many juveniles were taken from the BEAR. A small school of blue runners about 18 cm. long was seen at the Woods Hole docks, and at least two were taken on hook and line on September 29. Two others of about the same size were caught in the Quissett trap on October 2, and Mr. Benson reported that he had taken about half a bushel of about this length on September 23. In the past few years, *crysos* has been by far the most abundant *Caranx* in sizes large enough to be caught in traps or by hook and line in the Cape Cod area. I have seen many of them from 16 to 20 cm. long taken in Cape Cod Bay as well as on the south side of the Cape, while I have seen only one specimen of *C. hippos* in the same period. The latter has been listed as the most common jack in southern New England, but Mr. Nichols has told me that this referred mainly to very small individuals. The range of *C. crysos* extends northward to Nova Scotia.

Caranx hippos (Linnaeus).—An 18-cm. jack crevalle was taken in the Quissett trap on October 9. The species has been recorded from Lynn and Provincetown in the Gulf of Maine, and as far north as Nova Scotia. It was listed as common at Woods Hole. As mentioned above, however, in recent years I have found *C. crysos* in much greater numbers than *C. hippos* in the vicinity of Cape Cod.

Caranx ruber (Bloch).—Two bar jacks 9 cm. long were taken in a net from the BEAR on September 10 (39°13′N, 71°13′W), along with over 200 *C. crysos* and two *Seriola falcata*. As the most northerly records I have found for *C. ruber* are 38°07′N, 68°45′W to 37°12′N, 67°39′W, from Nichols (*loc. cit.*), this capture appears to represent a northerly extension of its known range.

Selar crumenophthalmus (Bloch).—Twenty-eight goggleye scad all about 16 cm. long were taken in the trap at Quissett from September 26 through October 9. The species has been listed three times from Cape Cod localities in the Gulf of Maine, and as far north as Cape Breton, Nova Scotia. It has been considered common in the fall at Woods Hole.

Alectis crinitus (Mitchill).—An 11-cm. threadfish was taken in the trap at Quissett on September 26. There are two records of the species from the Cape Cod area in the Gulf of Maine and it is listed as rare in New York and southern New England.

Coryphaena equisetis Linnaeus.—I have found only one previous record of the little dolphin from off the Atlantic coast[1] of the United States. This was listed by Linton (1905, Bull. U. S. Bur. Fish., 24 (1904): 373) from Cape Lookout, North Carolina (34°35′N). I was fortunate in obtaining a second such record while sport fishing off Cape Hatteras, North Carolina, on October 14, 1952. A 39-cm. specimen was taken from a large school of *C. hippurus* of about the same size. On October 16, 1953, a 40-cm. *equisetis* was taken from the ATLANTIS (38°22′N, 69°35′W), 135 miles south of Nantucket Light Vessel. This appears to be the most northerly capture of the species on record for the western Atlantic, although its close relative, *C. hippurus*, is sometimes abundant off southern New England and has been recorded from the Gulf of Maine and the outer coast of Nova Scotia.

I am indebted to Mr. W. C. Schroeder, Dr. Richard H. Backus, Dr. John Kanwisher, and others of the scientific staff of the Woods Hole Oceanographic Institution, to Captain W. Scott Bray and Boatswain Carl Speight of the ATLANTIS and other members of the personnel of the respective vessels, and to Mr. Norman Benson, for collecting these specimens, and to Mr. Schroeder and Mr. John T. Nichols, of the American Museum of Natural History, for their assistance in preparing this note.—FRANK J. MATHER III, *Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.* (Contribution No. 702).

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[1] In the Straits of Florida, however, the species appears to be fairly common. Al Pflueger, the well-known Miami taxidermist, has told me that these fish are frequently taken in the Gulf Stream off that port, where they are known as "pompano dolphin." He showed me a specimen at his shop, and has presented others to the Department of Zoology at Miami University.

Contribution No. 703

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Analysis and Data Problems in Relation to Numerical Prediction

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ABSTRACT

Instantaneous height tendencies computed from different analyses of the same 500-mb chart illustrate that discrepancies in analysis or observations can have a serious effect on the accuracy of numerical forecasts. The present status of the Northern-Hemisphere aerological network is reviewed, stressing the inhomogeneity of the radiosonde network, the need for observations in fringe areas surrounding the present dense networks, and the desirability of more radio-wind stations. The suggestion is made that machine prognoses incorporating variations of fictitious observations could be used to evaluate the improvements needed and the desirability of setting up new aerological stations in particular locations.

INTRODUCTION

THE development of numerical weather prediction [3] involves not only the problem of devising suitable physical models, but in addition throws increased demands upon aerological observations and analyses. While a few years ago it was regarded as sufficient to know the locations and general magnitudes of trough and ridge systems and the approximate mean strength of the westerlies, the newer methods involve evaluation of quantities depending upon the detailed pressure field. It is well recognized by those who work in numerical prediction that its further development, as in the past, will be dependent upon improvement of observations and analyses as well as upon the forecasting methods themselves. This paper is an attempt to evaluate the analysis situation in light of the present status of the aerological network.

INFLUENCE OF ANALYSIS QUALITY ON TENDENCY COMPUTATIONS

In a series of barotropic tendency computations at the University of Stockholm [12], the verification results varied widely for different pairs of 500-mb charts used. Although part of this variation was due to other factors, it was evident in a number of cases that the most serious defect was in analysis of the basic charts.

As an example, the 500-mb chart for 0300 GCT 15 November 1951 is shown in FIGURE 1a, with the computed instantaneous tendencies in FIGURE 1b. The mean of the tendencies computed from this chart and one 12 hours earlier is shown in FIGURE 2a, and the observed 12-hour height

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[1] Now at University of Chicago.

[2] Contribution No. 703 from Woods Hole Oceanographic Institution. Revised from Scientific Paper No. 4, first session of Commission for Aerology, World Meteorological Organization, Toronto, 1953. This paper was written while the author was employed under contract with the Office of Naval Research. It does not necessarily represent opinions or recommendations of the sponsoring agency.

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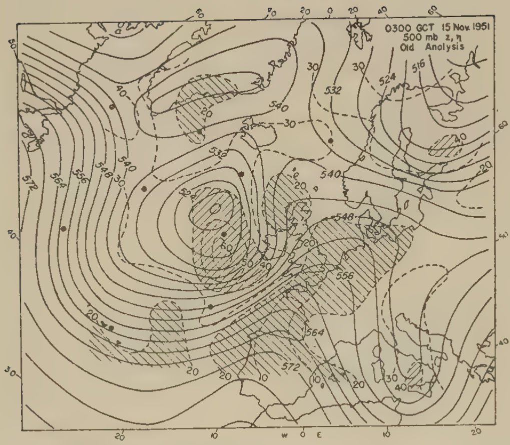


FIG. 1a. 500-mb chart, 0300 GCT 15 November 1951. Solid lines, height contours, tens of meters, interval 40 m. Dashed lines, geostrophic absolute vorticity (in units designed for the tendency computation scheme, roughly equivalent to 0.5×10^{-5} sec^{-1}). Areas of vorticity exceeding 40 units hatched upward toward right; less than 20 downward toward right. Heavy dots show locations of available aerological observations (radiosonde and rawin) at ocean stations.

changes in FIGURE 2b. Correspondence between computed and observed changes was extremely poor, the correlation coefficient (for grid points inside the central rectangle) being only 0.06. The chief error lies in the pronounced computed rise area in the southwest corner of FIGURE 2a, which does not appear at all in the observed changes.

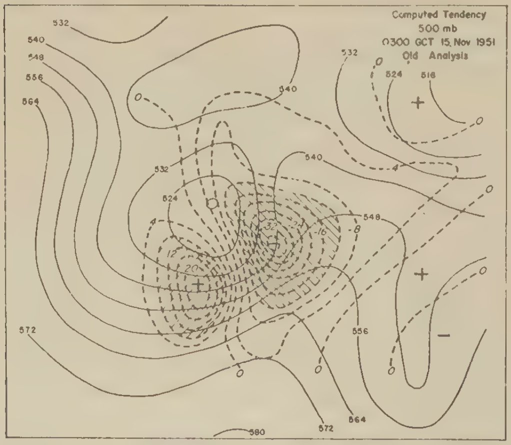


FIG. 1b. Contours of 500-mb surface and instantaneous tendency (dashed lines, tens of meters per 12 hr) computed from FIGURE 1a. Rises exceeding 80 m per 12 hr and falls greater than 120 m per 12 hr are hatched.

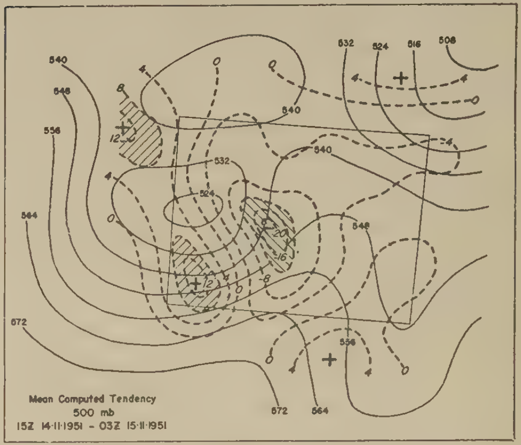


FIG. 2a. Mean of tendencies computed from 500-mb charts at 1500 GCT 14 November and 0300 GCT 15 November 1951. Legend as in FIGURE 1b. Central rectangle shows boundary of verification region.

Of the pair of computations averaged, the tendencies from the chart shown in FIGURE 1 contributed by far the greater share to the discrepancy in results.

Examination of the original analysis (FIG. 1a) discloses the source of the apparent error in the tendency field, in the strong vorticity advection indicated south of the central cyclone. This peculiarity is due largely to variations of the horizontal wind shear because of alternate difluence and confluence of the analyzed contours, which results in alternately maximizing and minimizing the vorticity flanking the jet stream in an exaggerated manner.

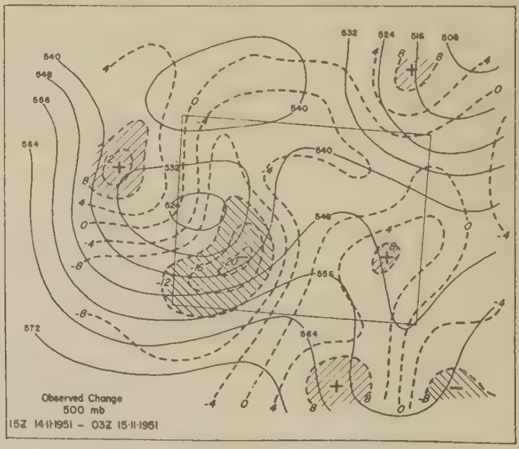


FIG. 2b. Observed local height changes during 12-hour period corresponding to FIGURE 2a.

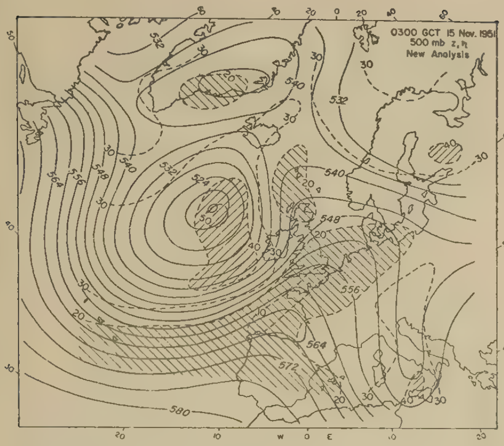


FIG. 3a. Re-analyzed 500-mb contours and vorticity field, 0300 GCT 15 November 1951. Legend as in FIGURE 1a.

FIGURE 3a shows a re-analysis of the 500-mb chart of FIGURE 1a. By drawing the contours so as to minimize the arbitrary variations of geostrophic wind along the streamlines, the strong advective decrease of vorticity south of the major low has been virtually eliminated without altering the reported height value at any observing station. The greatest difference between *analyzed* height values anywhere on the charts of FIGURES 1a and 3a is 40 m (130 ft). However *the greatest computed rising tendency decreased from 220 m to 20 m per 12 hr, and the maximum computed fall decreased from 370 m to 240 m per 12 hr* (FIG. 3b, *cf.* FIG. 1b).

The new tendency field, when averaged with the one 12 hours earlier, showed the same broad features as in FIGURE 2a; however the maximum fall center (located too far northeast) decreased by 80 m while the maximum rises shifted 500 km northwest and decreased by 80 m, a substantial part of the questionable rise area in FIGURE 2a being replaced by falls. A re-analysis of the first map with a more careful eye to continuity would result in a considerable further improvement of the results. In spite of the probable analytical errors still residual in the first chart of the pair, *re-analysis of the second chart alone raised the verification correlation coefficient from 0.06 to 0.41.*

It is not possible, without actual tests, to say how large the final forecast error would be if made in iterative short time-steps. However, it seems clear that analytical errors could have a very serious effect upon numerical prognoses, entirely aside from discrepancies arising from computational errors or the choice of mathematical models. Although the re-analyzed area lies over the Atlantic Ocean, essentially the same sort of result could be encountered over land areas, if too strict reliance were placed on erroneous radiosonde observations in a denser network. According to Bolin and Charney [2], only a small average improvement in forecasts was obtained by re-analysis of the charts initially used for an extensive series of barotropic computations made at Princeton. However, the principal area involved has a rather dense and relatively homogeneous upper-air network, limiting the possibility of very large changes in analyses without discarding observations. The computations at Stockholm, involving partly an oceanic region and partly a network inhomogeneous in radiosonde type, were much more subject to differences in analysis interpretation.

THE ANALYSIS PROBLEM

An immediate and extensive appraisal of all aspects of the data and analysis problems is vitally needed, if optimum results are to be obtained from numerical forecasting advances. The above example illustrates that analyses adequate for subjective forecasting techniques may be inadequate for the more refined methods of numerical prognosis, from which more is expected.

While computations in ordinary forecasting practice usually involve at most a first differentiation of the contour field (often averaged in time or space), machine computations involve second or higher differentiation and are much more sensitive to details of the analysis.

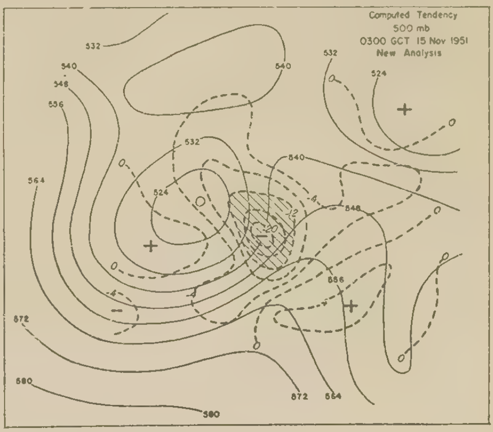


FIG. 3b. Tendencies computed from chart of FIGURE 3a. Legend as in FIGURE 1b.

Although a simple prognosis can be made in a few minutes to a half hour after data are fed into an electronic computer [3, 10], collection and analysis of the observations take several times as long. The time required for analysis becomes a disproportionately large part of the forecast period, if complex models are used which require mutually consistent analyses at a number of levels. Thus a very definite need is felt for developing new methods of data processing. This problem has been discussed in some detail by Smagorinsky [10].

Data processing may be divided broadly into the phases of observation, communication, and plotting and analysis of data. Hope is envisioned in some quarters for an eventual integration of these three phases, but the sheer mass of equipment involved makes it virtually certain that only piecemeal combinations will take place in the near future.

Communication consumes a very considerable portion of the total time occupied by the data processing cycle. Smagorinsky [10] contrasts the time of 6 minutes required for a simplified 24-hour machine prognosis (using a single-layer model with certain approximations) with the minimum of 3½ hours after release time taken to collect the "first transmissions" of aerological observations, and 6¼ hours for collection of higher-level data. Although map analysis itself clearly does not unmitigatedly bear the blame for the large amount of time consumed in data processing, the fact that communication is so slow makes it imperative that the time spent in actual analysis be cut down as much as possible.

Naturally the unprecedented demands on both quality and speed have led to emphasis on the development of objective analysis techniques, for which a rational approach was advanced by Panofsky [8]. Among the projected advantages of objective analysis are:—

1) Economy of time and enlargement of capacity,
2) Improvement of quality, including elimination of preconceptions or habits of analysts which adversely color the character of the analyzed field,
3) Smoothing of analysis and elimination of "local disturbances" not considered representative or significant, and
4) Elimination of the time-consuming process of reading off and punching data to be fed into machine.

Among the obstacles to successful objective analysis are:—

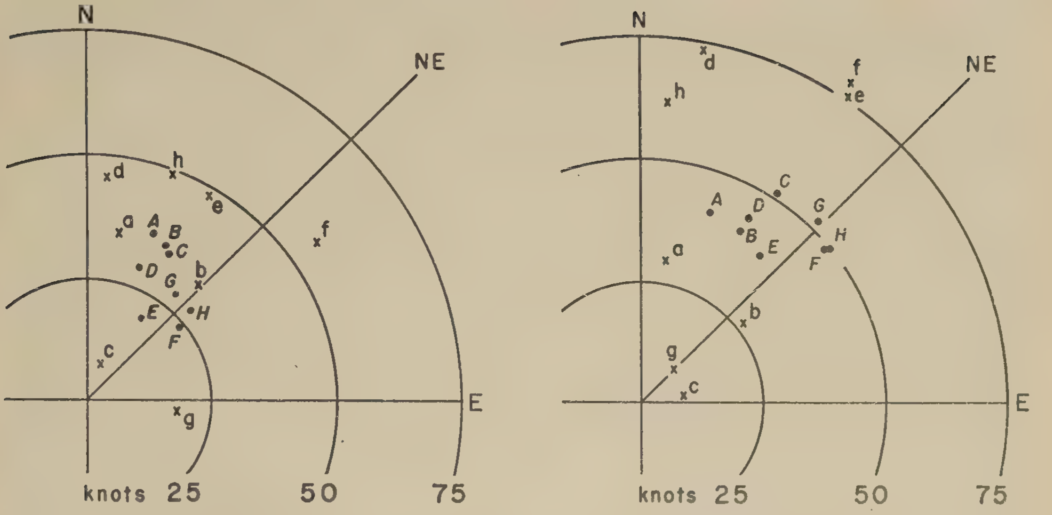
1) Inadequacy in quantity of observational data,
2) Erroneous observations and communication errors,
3) Limited knowedge of atmospheric structure and difficulty of incorporating "models" of structure which are readily used by subjective analysts,
4) The possibility that the instructions inherent in objective methods may result in the adoption of "habits" deleterious to the quality of the analysis.

One of the most serious problems is that of dealing with erroneous observations. Present methods (e.g., fitting by the method of least squares) tend to smooth out errors but at the same time may result in incomplete use of good observations. It is of the utmost importance that the root of the difficulty, the deficiencies of the observation network itself, be attacked and that positive recommendations be made for its improvement considering the particular needs of numerical prediction. In the following, certain aspects of the present data situation will be reviewed.

ACCURACY OF OBSERVATIONS

A few years ago, most routine upper-air analysis was carried out at 700 mb or lower, where errors in height determination are not usually large. With the development of forecasting techniques using information at higher levels, the effect of height-cumulative observation errors has become increasingly serious.

The effect of such errors on objective computation of the wind field is well illustrated in a recent article by Hovmöller [5]. FIGURE 4, adapted from his paper, shows a comparison between observed and geostrophically computed winds over England at 1500 GCT 29 May 1951 (a random case). No comment is necessary except perhaps to point out that, at both 500 and 300 mb, all computed winds lie outside the envelope of the mean observed wind values. Since the error in computed geostrophic wind varies inversely with the distance between stations for a given height error, it is questionable whether much is to be gained (from the point of view of determining the contour field) by increasing the density of the radiosonde network in regions where the network is already fairly dense. It should be noted that the network involved above is homogeneous as to radiosonde type (no comparisons of this kind are available for other types of radiosonde).



(a) 500 mb. (b) 300 mb.

Fig. 4. Comparison of observed and geostrophically-computed winds over British Isles, 1500 GCT 29 May 1951 (adapted from Hovmöller [5]). Each cross with small letter indicates geostrophic wind computed from height values at three stations, and the dot with corresponding capital letter shows the vector mean of the three direct wind observations at the same stations. (a) 500 mb; (b) 300 mb.

Inhomogeneity of Instrument Type

Particularly over Europe, but in parts of North America as well, the type of radiosonde varies over short distances. This inhomogeneity makes it impossible to place a strict interpretation upon an analysis of the contour field.

For the purpose of comparing instruments, a series of tests was made at Payerne, Switzerland, in May 1950. Two to six radiosondes of different types (Finnish, Swiss, French, United Kingdom, U. S. Zone of Western Germany) were released on the same balloon train in each test, with 25 train ascents in all. Figure 5 (adapted from [6]) shows the computed heights for all ascents, at the 500-mb level. The mean total spreads of computed heights were: 36 m at 500 mb, 79 m at 300 mb, and 120 m at 200 mb, the maximum differences obtained on any ascent being about twice these values.

A similar series of tests was made at Oklahoma City, Oklahoma, in June 1951 [11] involving five types of instruments used by the U. S. Weather Bureau, Air Force, and Navy. For the 850-, 700-, 500-, and 400-mb levels combined, 81 per cent of the computed heights agreed within 20 m and 96 per cent within 40 m. The variations increased markedly above 400 mb.

In the absence of a sufficient number of comparisons of identical instruments, it cannot be determined to what extent the above comparisons reflect incompatibility of different types, or random errors of individual types. However, there are clear indications that significant incompatibility exists. The acceptability, for synoptic purposes, of the indicated degree of agreement can be questioned since, for example, in the Oklahoma tests, 19 per cent of the computed heights of constant pressure surfaces at 400 mb or below differed by more than 20 m. At latitude 45°, if the geostrophic vorticity is computed from a grid of stations 400 km apart with a 20 m error at the central grid point, an error in vorticity of 0.5×10^{-4} $\sec^{-1}$ results (*cf.* [5]), hardly an insignificant amount since the absolute vorticity does not ordinarily exceed six to ten times this value.

The Hemispheric Observation Network

The aerological network of the Northern Hemisphere, although undergoing continual improvement, is still markedly deficient in certain respects. Examination of a typical upper-air coverage[3] shows that a reasonably dense radiosonde network is available over practically the whole area north of latitude 30°, with the exception of China and extensive parts of the Pacific Ocean. There are,

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[3] See, e.g., example given in [7]. Except for certain aircraft reconnaissance flights and a few stations missing due to communications, this example is still representative.

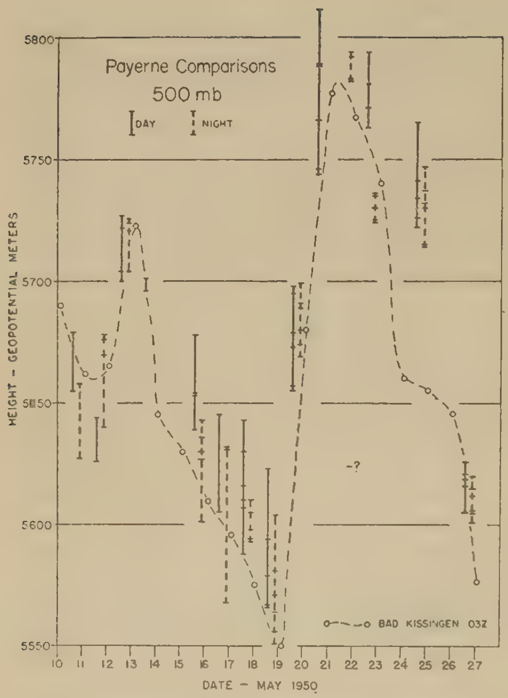

FIG. 5. Comparison of 500-mb heights computed from simultaneous radiosonde ascents, Payerne, May 1950 (adapted from Malet [6]). Ordinate height (geopotential meters); abscissa, day of month. Heavy vertical lines, range of heights indicated by train of instruments on same balloon (day, solid; night, dashed); short horizontal marks show heights given by individual instruments. Thin dashed line shows trend of heights at same location from 0300 GCT charts analyzed at Bad Kissingen.

however, several very large regions with no consistent high-level wind coverage at all. This very seriously impairs the usefulness of the existing radiosonde stations.

Eliassen[4] has estimated that "a station distance of about 300 km between radiosonde stations without wind measurements, and 500 km between stations with wind measurements, would define the contour fields in sufficient detail [for numerical forecasting purposes], provided there were no observation errors." The urgent need for more all-weather wind stations arises from the fact that in some regions it would be prohibitively expensive to increase the radiosonde network to the required density, while in others the existing network is of such poor quality (due to a combination of inhomogeneous instrumentation and excessive random errors) that discrepancies cannot be adequately screened without the help of wind measurements.

Namias and Clapp [7], drawing attention to the concentration of observations in certain regions, have suggested that "it would appear preferable to reduce the amount of data in populated areas and use the money thus saved to increase the number of reports, particularly upper-air reports, from remote areas." While a certain concentration is desirable in the regions most frequented by synoptic disturbances, the present underdevelopment of the net work in certain areas closely bounding the population centers is a matter of serious concern.

Aside from the oceans, the principal deficiency is in subtropical latitudes. Although aerological networks exist in India, Mexico (no rawin stations) and the Caribbean area, and the Pacific Islands, other regions south of latitude 30° are almost totally unexploited. The need for extending the network in subtropical latitudes is emphasized by observational studies [9] which indicate that the tropics play an important part in the development of middle-latitude flow patterns, and by the fact that during the cooler seasons the strongest winds aloft are located on the average around latitudes 25°–30° where at present there are very few rawin stations. Practicing synoptic analysts are familiar with the fact that, both in North America and in Europe, the upper-level wave patterns associated with characteristic middle-latitude disturbances often extend well south of latitude 30°, where the lack or inadequacy of data makes their structure quantitatively undefinable. Augmentation of the network, particularly of rawin stations, down to at least latitude 20°, should be given top priority in the observational program.

In addition, installation of rawinsonde stations on some islands such as Guadalupe, Funchal (now a radiosonde station), one of the Canary Islands and Majorca, and replacement of the present station at Lagens by two stations in the Azores (whose extreme islands are 600 km apart) would considerably augment the area of reliable analysis for numerical forecasting purposes. International financing would naturally be required.

Since the oceans will never be blanketed by a thick network of weather ships, ocean analysis must continue to rely upon full usage of aircraft observations and study of time-variations at the existing ship stations. To derive optimum benefit from these stations, a return to the former schedule of four complete aerological ascents daily is desirable. Cost of the additional radiosonde observations would be small compared with the basic cost of maintaining the ships on location.

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[4] A. Eliassen, "On the demands upon the aerological network from the viewpoint of numerical forecasting," a lecture given at Meteorological Conference at University of Helsinki, 20 May 1953; abstract in *Geophysica*, vol. 4, No. 3, p. 144.

Determination of Observational Requirements

It would obviously be impractical to experiment on a large scale with projected improvements of the aerological network by actually adding and removing stations until an optimum state is reached.

An alternative expedient would be to experiment with machine prognoses using charts constructed partly from fictitious observations, and comparing (as in Figs. 1 to 3) the prognoses obtained from analyses of different spot values (heights and/or winds). Such experiments should include tests to determine:

(*1*) where stations should be added on the fringes of present dense networks (e.g., in subtropical latitudes, testing specific cases where "middle-latitude" flow patterns extend far south and the analysis is doubtful);

(*2*) the effects of different possible interpretations of existing data, with particular regard to stations suspected of being consistently incorrect on a day-to-day basis;

(*3*) the required accuracy of radiosonde data in a dense network (by analyzing exactly for existing observations, then varying these by applying random probable errors within present manufacturing specifications);

(*4*) the network density required for satisfactory objective analysis (fitting networks of different densities to a smoothed field, applying random errors to the fictitious observations, objectively analyzing the results and comparing prognoses).

From the results of extensive tests of the sort outlined above, covering a variety of synoptic situations, really specific recommendations for changes in the aerological network could be made. Since the method would be objective, the need for the recommended changes could be justified by their demonstrated effects upon actual forecasts.

Desirability of Code Changes

The present transmission codes for aerological data are in some respects inadequate for numerical forecasting or other analysis purposes. Emphasis in the present upper-wind codes, for example, is toward detailed reports in the lower levels, while in fact most forecasting methods now are concerned largly with the higher-level flow patterns where reported wind levels are far apart. Full usage of the optional WMO provision for "significant levels" showing marked change in vectorial wind velocity (to be implemented in 1955) should largely alleviate this deficiency.

Since present numerical forecasting models normally deal with assumed mean conditions in a finite layer of the atmosphere which may be 100 mb or more in depth, an addition to the code of actual mean winds through such layers, made at the aerological stations, should be considered. Such mean winds should naturally be used in conjunction with mean stream functions for the same layer, also transmitted in the radiosonde code. Probably the most convenient representation of the mean stream function would be the layer mean of the quantity D (departure from standard atmosphere height) recommended by Bellamy [1]. It is very likely that the use of layer-mean winds (e.g., 450 to 550 mb or 400 to 600 mb instead of point values at 500 mb) would result in a significant improvement in the quality of analyses. The present single-level reporting often results in the selection of non-representative wind speeds from erratic velocity profiles plotted at the sounding stations which contain real or erroneous fluctuations that cannot be followed in synoptic continuity; often selection of the wind speed at a slightly different level would give significantly different results. It is likely that many of the irregularities met in isotach analysis arise from this cause. The encoding of wind direction to the nearest degree, or five degrees, would also be desirable since with strong winds coding in tens of degrees may result in a significant vectorial velocity error. Coding to five degrees could be accomplished, e.g., by addition of 50 to the wind direction, without increasing message length.

The large transmission time for aerological messages is, as Smagorinsky [10] has illustrated, due primarily to their sheer bulk. Gilchrist and Cressman [4] have shown that by using a 27-character (including letters) system the wordage can be cut down very considerably (e.g., a radiosonde message of 29 groups in the present code can be cut without loss of information to 18 groups). The eventual adoption of some such system seems an inevitable necessity.

Conclusions

Extensive experiments have already demonstrated that highly useful forecasts of the flow pattern can be made by numerical methods. Further improvement of the accuracy of such forecasts will depend not only upon the development of realistic physical-mathematical models, but also very strongly upon an increase in the quality of the aerological network. Immediate steps should be taken to determine, through practical experiments, the needed improvements.

The obvious neds are for increased standardization of radiosondes, establishment of aerological stations on the fringes of the existing network (particularly in the subtropics), and a marked increase of reliable all-weather winds-aloft stations. Particular emphasis should be placed on radio-wind observations (off airways as well as on) since these are absolutely essential for delineation of the flow pattern both where the radiosonde network is sparse and where instruments give inhomogeneous results.

It is questionable whether the present network is adequate for application of purely objective analysis methods, except in very restricted regions. Subjective analysis will probably remain, for some time to come, a necessary step in screening errors and in outlining the structure of flow patterns in regions with sparse data. On the other hand, very complete and careful manual analysis is clearly too slow for numerical forecasting purposes. It should be possible to find a way of automatically or semi-automatically scanning rudimentary subjective analyses and fitting the data thus obtained into an objective analysis system, thereby making use of the particular advantages of both systems.

ACKNOWLEDGMENTS

This paper was written as a result of a suggestion by Prof. C.-G. Rossby, and was instigated largely by a request for opinions on data needs, expressed by Prof. J. Van Mieghem, President of the Commission for Aerology, World Meteorological Organization. I gratefully acknowledge a series of conversations with them which helped me in formulating the paper. I wish to record that some of the views expressed herein overlap those presented in a talk by Dr. A. Eliassen on 20 May 1953 (see footnote 4).

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Contribution No. 705

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ON THE RESPIRATION IN SCALLOPS (LAMELLIBRANCHIATA)

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ON THE RESPIRATION IN SCALLOPS (LAMELLIBRANCHIATA)[1]

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The only data in the literature on the respiration of scallops seem to be those of Spärck (1936; *cf.* also Thorson, 1936), who determined the oxygen uptake in *Pecten groenlandicus* (arctic), *P. varius* (boreal-mediterranean), and *P. flexuosus* (mediterranean) in nearly air-saturated water. This author found that the resting metabolism of the scallops, and other bivalves which have a marked capacity for rapid swimming locomotion, is considerably higher than that of more sedentary types.

The present paper reports on a study of the respiration in the deep sea scallop and the bay scallop, both of common occurrence and of considerable economic importance along certain areas of the Atlantic coast of North America. The oxygen consumption of resting (non-swimming) individuals was determined over a range of concentrations of oxygen of about the air-saturation value to close to zero. In addition determinations were made, in aerated water, of the oxygen utilization or the percentage of oxygen removed from the inspired water during its passage through mantle cavity and gills.

MATERIAL AND METHOD OF OXYGEN ANALYSIS

The deep sea scallops (*Pecten grandis* Solander) were taken from Cape Cod Bay, at a depth of about 12 m., the bay scallops (*Pecten irradians* Lamarck) from a shallow salt water pond near Woods Hole. All animals were kept in the laboratory in tanks with running sea water (salinity 31–32.5‰). For the experiments, which were carried out during June and July, 1952, and from September–November, 1953, only specimens that were in apparent good health, showing a wealth of actively moving, extended tentacles and production of faecal material, were used.

Analyses of dissolved oxygen were made by the Winkler method on samples of about one ml. (van Dam, 1935a).

TECHNIQUES OF MEASUREMENTS OF O_2-CONSUMPTION

(a) Continuous measurements of O_2-consumption in water approximately saturated with air were performed on single individuals of the sea scallop by means of a volumetric respirometer technique as described by Scholander (1949). In this method the oxygen consumed is directly read on a syringe from which oxygen is introduced into the system at the rate at which it is removed by the animal.

A plastic box of about 900 ml. capacity, immersed in a water bath, was used as a respiration chamber. It was filled with about 850 ml. of sea water which had been filtered through cotton or glass wool. Prior to the actual experiments the animals were kept for one hour or longer in the respirometer running open to the air. Runs without an animal in the water showed a blank oxygen consumption of, on the average, about 0.2 ml. O_2/hr. (Fig. 5). The cause of these rather high blank values is not known. The calculated Q_{O_2}-values (O_2-consumption per kg. and hour) given in Figure 4 are STP- and blank-corrected. In a number of tests initial and final O_2-content and approximate pH (Hellige comparator) of the water in the respirometer were determined, showing that, as a rule, the O_2-content remained practically constant. In a few cases a decrease of 0.1–0.3 ml. O_2/L. was observed, and the Q_{O_2}-values were corrected accordingly. Although in this method the CO_2 produced is continuously being removed, the pH of the water during the tests usually decreased from about 8 to about 7.2–7.6. This, however, as can be seen from Figure 5, had no apparent effect on the rate of oxygen uptake. The same holds for the experiments with the closed respiratory chamber technique described below, in which all excreta, CO_2 included, remained in the water.

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[1] Contribution no. 705 from the Woods Hole Oceanographic Institution.

(b) To determine the critical O_2-tension, measurements of O_2-consumption were made in closed plastic respiration chambers of 1–3 L. capacity (Fig. 1), completely filled with water, in which the concentration of oxygen decreased progressively due to the respiration of the animal.

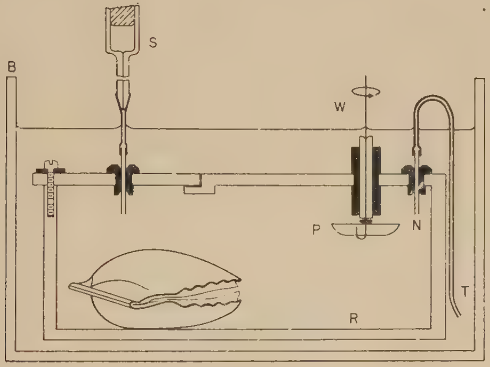

FIGURE 1. Diagram of closed respiratory chamber (R). W, P: stainless steel drive shaft and plastic paddle. T, N: small bore plastic tubing and needle through which water from water-bath B enters R when water samples for O_2-analysis are taken with syringe S.

Blank runs (Fig. 6) showed that in the absence of an experimental animal the O_2-content of the water in the respirometer was practically constant at any O_2-tension. Control tests showed that the Winkler procedure, as such, was not interfered with by metabolites in water in which animals had been confined for several hours.

Prior to the O_2-uptake measurements the animals were scrubbed clean thoroughly and acclimated to the experimental temperatures for one day or longer. To determine the wet weight of the soft tissues, the animal was opened by severing the adductor muscle. Then all soft tissues were taken out of the shells, drained for about 5 minutes, dried at the outside on filter paper and then weighed. Length and weight of the animals used are given in Table I.

TECHNIQUE OF DETERMINING THE OXYGEN UTILIZATION

The sea scallops were lying freely in a normal position, *i.e.*, on the right valve, on the bottom of an all-glass aquarium. Samples of the inhalant water current were taken with a syringe, the tip of which was placed near the pallial opening opposite the middle of the hinge. Simultaneously, samples of the exhalant current were taken, either directly by means of a syringe to which a fine glass tip, bent at right angles, was attached (animals no. 1 and 5, 18 samples), or by means of a siphon as indicated in Figure 2 (animal no. 6, 12 samples). Glass tip or siphon were introduced about 5 mm. into the cloacal chamber. Water from the cloacal cavity was allowed to pass through the siphon (capacity 7 ml.) for about one hour, at a rate of 1.5 ml./min., before the first samples were taken. There were no signs that the presence of tip or siphon, which, as a rule, did not touch the animal's tissues, interfered with the normal vigorous propulsion of water. Slowness of sampling guaranteed that the sample was not contaminated with outside water. A continuous flow of fresh sea water combined with an intensive stirring by means of big bubbles

TABLE I

*Length and weight of experimental animals**

Specimen no.	Number of test in which specimen was used		Length (mm.)	Wet meat (gms.)	Total wet weight (gms.)
	Test no.	Fig. no.			
		Sea Scallop			
1	—	—	146	—	—
2	1–4	5	59	9	25.0
3	7, 8	5	63	10.5	29.5
4	5, 6	5	69	13.5	40.0
5	9–13	5	81	23.0	88.0
6	14, 15	5	75	18.0	50.0
7	7, 8	6	73	17.8	49.0
8	1, 2	6	101	34.5	110
9	3, 6, 9	6	139	78.8	294
11	11	6	130	60.3	235
		Bay Scallop			
1	—	—	56	6.4	31.9
2	—	—	56	7.0	33.5
3	4, 10	6	61	10.2	38.1
5	5, 13	6	63	12.5	39.0
6	5, 12	6	59	10.5	33.8

* The length given here denotes the straight-line distance between the middle of the hinge (p) and a point at the margin of the upper shell opposite p. Due to circumstances, the wet meat weight of the sea scallops 2, 3, 4, 5 and 6 was not determined directly but was taken from a graphic representation of data, collected by Mr. J. A. Posgay, relating length and weight of wet meat in over one hundred specimens.

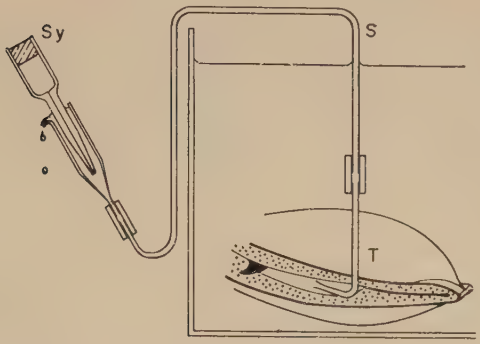

FIGURE 2. Sampling from the exhalant water current in the sea scallop by means of a cloacal siphon. From the continuously overflowing water, samples of about one ml. are taken with a syringe pipette (Sy). The lower end of the glass tube T is about 5 mm. inside the (white) cloacal chamber. Stippled: mantle. Black: tip of gills. Diagram.

of air kept the O_2-content of the water in the experimental aquarium uniform over prolonged periods of time.

In the earlier studies of the oxygen utilization in Lamellibranchia, made on siphonate forms, it has been assumed that, due to turbulent mixing in the relatively long and narrow siphon, the oxygen in the water leaving the exhalant aperture is fairly uniformly distributed. In the scallops, however, as in many other species, a siphon is lacking and the cloacal chamber communicates with the exterior through a normally widely opened slit. To determine whether appreciable O_2-gradients occur in the broad ribbon of water escaping from this slit, in the bay scallop two or three samples were taken simultaneously at different spots. The technique used is indicated in Figure 3.

As a rule the introduction of the needles into the cloacal cavity disturbed the ventilation only during the first few minutes and in several cases was accomplished

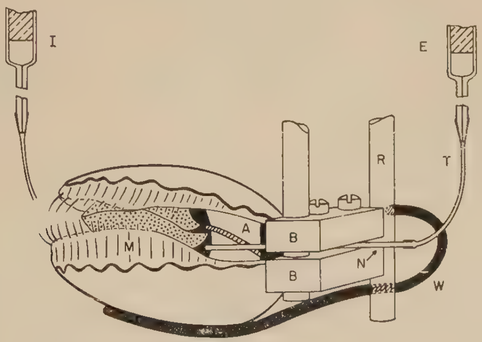

FIGURE 3. Sampling from the exhalant water current in the bay scallop by means of 2 or 3 needles (N), held, in a parallel fashion, 3–10 mm. apart, in a plastic block (B). The needles, of which only one is shown, protrude $\frac{1}{2}$–$1\frac{1}{2}$ cm. into the cloacal chamber (black), and are connected with a sampling syringe (E). The scallop is paraffined onto a piece of wire (W), held in a plastic rod (R). I: One of the two syringes, sampling simultaneously, at different spots, from inhalant current. M: mantle. Stippled: gills. A: adductor muscle. Hatched: intestine, opening, at the left hand side, into the cloacal chamber (black). Diagram.

without any visible reaction on part of the animal. Moreover, sampling was not begun until after at least one hour had elapsed. On several occasions the needles were left in position overnight. By manipulating two syringes at a time and changing over from one pair to another every 10 seconds, simultaneity of sampling was accomplished to a fair degree. Sampling was interrupted when an animal would interrupt the pumping and was only resumed a couple of minutes after normal ventilation had begun again.

Discussion of Results

(*a*) *Oxygen consumption in approximately air-saturated water*

In Figure 4 the values for the oxygen consumption of the sea and bay scallop obtained in the present study (dots and crosses, respectively) are compared with data on the oxygen uptake of various other marine Lamellibranchia selected from the literature. The latter were grouped together and averaged according to geographical distribution (arctic, boreal, and mediterranean) and locomotory faculties (swimming versus non-swimming) of the animals. The relation between these

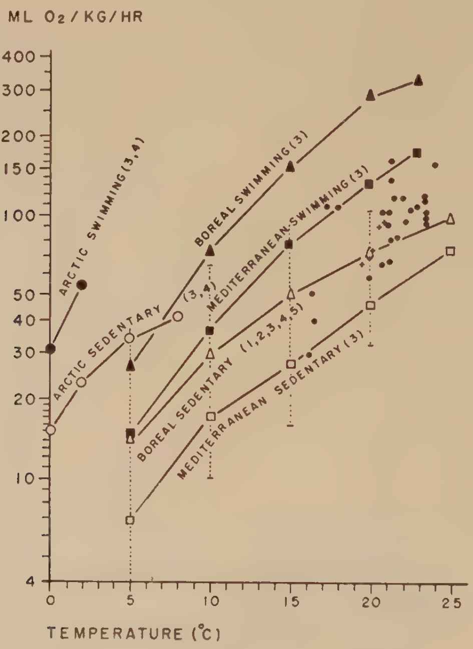

FIGURE 4. Oxygen consumption of resting specimens of bay and sea scallop studied in the present paper (crosses and dots, respectively) compared with the oxygen uptake of other marine Lamellibranchia, selected from the literature and grouped together according to geographical distribution (arctic, boreal and mediterranean species) and according to locomotory faculties (swimming or more or less sedentary species). On the curves, the points represent the arithmetical mean of all Q_{O_2}-values available for a given temperature. The figures in brackets refer to the source in the literature from which the data, used to compute these mean values, were taken, as follows: 1 = Bruce, 1926; 2 = Thamdrup, 1935; 3 = Spärck, 1936; 4 = Thorson, 1936; 5 = Whedon and Sommer, 1937. Vertical, stippled, lines: spread of data in the group of the boreal sedentary species.

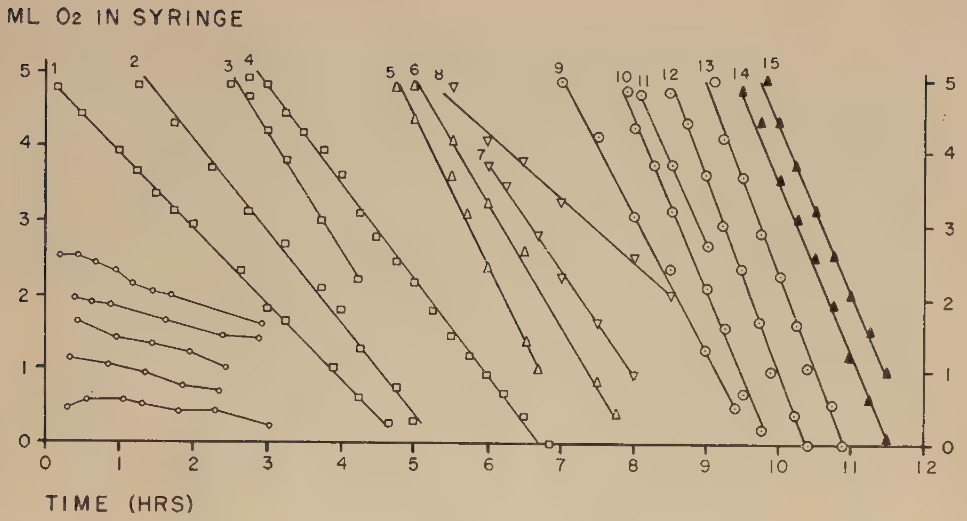

FIGURE 5. Rate of oxygen uptake in the sea scallop in approximately air-saturated water. Ordinate: amount of oxygen (ml.) in the measuring syringe. Abscissa: time (hrs.). Numbering of tests as in Table I. Small circles: blank runs.

factors and the metabolic rate in marine Lamellibranchia has been dealt with already by Spärck (1936). The following data (adult specimens, outside the spawning season) were used: Spärck (1936): 9 arctic, 12 boreal, and 11 mediterranean species; Thorson (1936): 11 arctic species; Thamdrup (1935): 3 boreal species; Bruce (1926): one boreal species; and Whedon and Sommer (1937): one boreal species. The figure indicates that the O_2-consumption in the bay scallop is essentially the same as that in the sea scallop. Over the range of temperatures investigated (16–24° C.), the O_2-uptake in these species is somewhat intermediate in position between the O_2-uptake of mediterranean scallops and that of more sedentary bivalves from that area and thus is about the same as the O_2-uptake of the average boreal non-swimming lamellibranch. In using the curves in Figure 4 as a basis for comparison, it must be borne in mind, however, that they give a greatly simplified picture inasmuch as the data, from which they were computed, show a very considerable spread in most cases. The spread in the Q_{O_2}-values of the different species of lamellibranchs in the boreal-sedentary group, is indicated in the figure (stippled lines). Not enough data are available to establish, in the bay and sea scallop, a relation between Q_{O_2} and season or size, or to estimate Q_{10}.

For several species of bivalve molluscs, lengthy periods of stoppage of the water propulsion have been reported in the literature. To the list of species given by van Dam (1938, p. 123; *cf.* also Verwey 1952, pp. 189–193) can be added *Venus mercenaria* (Collip, 1921; Chipman and Galtsoff, 1949) and *Hyridella australis* (Hiscock, 1950; 1953). Persistence of rhythmicity in O_2-uptake in molluscs under laboratory conditions was further reported by Gompel (1937) and by Sandeen *et al.* (1953), and in the rate of water propulsion in the California mussel by Rao (1953). No prolonged interruptions of the ventilation were observed in the scallops and the oxygen uptake of the latter, accordingly, appears to be quite uniform (Figs. 5 and 6). Also, as already mentioned by Spärck (1936), scallops cannot be kept out of water for nearly as long a time as many other bivalves, without being damaged. When kept in moist air at room temperature they soon open their valves and gradually lose the typical reaction to the sudden cast of a shadow which consists of a vigorous closing movement. The oxygen consumption determined in a sea scallop which had been subjected to such a treatment for seven hours appeared to be low for the temperature of the test (74 ml. O_2/kg./hr., 22.7° C.), the critical oxygen tension high (test 3, Fig. 6). During this test the animal held its valves abnormally wide apart and its gills were arranged in a disorderly fashion.

(*b*) *Oxygen consumption at progressively decreasing concentrations of oxygen*

With not too rapid a fall in the oxygen content of the inspired water, the scallops appeared to be capable of maintaining a normal oxygen uptake down to a concentration of oxygen of about 1.0–0.5 ml. O_2/L. (Fig. 6). Similar findings have been reported for other species of Lamellibranchiata (Weiland, 1919; Nozawa, 1929; Galtsoff and Whipple, 1930; Ishida, 1935; Thamdrup, 1935; Whedon and Sommer, 1937; Hers, 1943). To what extent this faculty is based on an increase in the amount of water pumped or on an increase in the percentage oxygen utilization, has not been investigated. It was noticed that the animals, in water poor in oxygen, display little or no active motion, gradually lose the "shadow-cast reaction," and erect the pallial velum in a vertical fashion. It is possible that the vigorous stirring of the water in the respiration chamber has contributed to some extent to the ventilation of the animal's tissues with water and thus has lowered the critical oxygen tension below a level which would prevail if this ventilation depended solely on the currents generated by the animal itself.

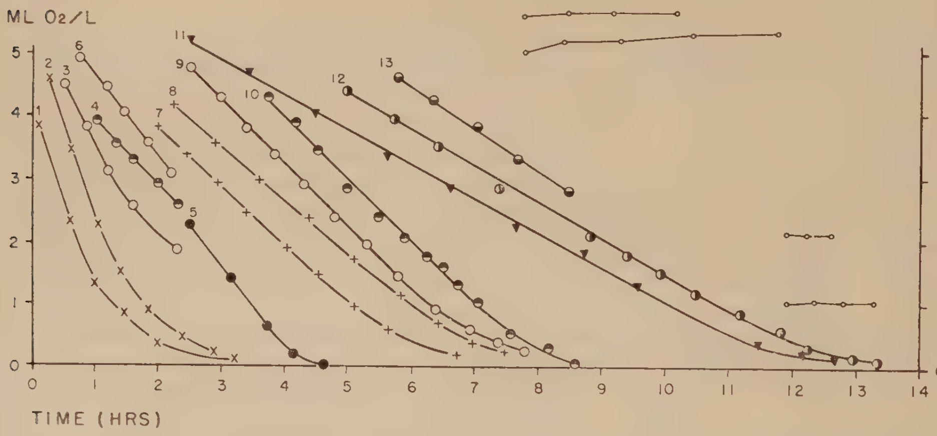

FIGURE 6. Rate of oxygen uptake of the sea scallop and of the bay scallop at progressively decreasing tensions of oxygen. Ordinate: O_2-content of water in respiratory chamber (ml. O_2/L.). Abscissa: time (hrs.). Numbering of tests as in Table I. For discussion of test no. 3, see text. Small circles: blank runs.

(*c*) *Oxygen utilization*

In the sea scallops the oxygen utilization was found to range from about ½ to 9%; in four out of the five bay scallops investigated the values represent a range of about 1 to 13% (Table II). Similarly low values have been found in siphonate Lamellibranchia and in several other filter feeding animals (van Dam, 1935b, 1938; Hazelhoff, 1938). Low values are also obtained for the oxygen utilization calculated from data on oxygen consumption and rate of water propulsion as given for a number of filter feeders, e.g., by Jørgensen (1952). It seems, then, that true filter feeders normally pump large amounts of water (*cf.* also Loosanoff and Nomejko, 1946; Owen, 1953), from which only a small fraction of the dissolved oxygen is being consumed. It would be of interest to determine the oxygen utilization or the rate of water propulsion in those species of bivalves which are not true filter feeders as, for example, those feeding on bottom deposits (cf. Yonge, 1953).

TABLE II

*Percentage oxygen utilization in the sea scallop**

O_2-content of inhaled water about 5 ml. O_2/L. Temperature about 17–22° C.

Specimen no. 1	Specimen no. 5	Specimen no. 6
2.9	7.5	1.9
2.2	6.4	2.7
0.7	5.2	0.8
1.6	7.6	3.6
1.6		2.3
1.6	Mean: 6.6%	2.3
4.0		2.9
8.8		3.4
1.8		1.9
4.0		3.8
2.2		3.8
2.2		3.8
0.4		
1.0		Mean: 2.8%
Mean: 2.5%		

* Except for one (Specimen no. 4, utilization 0.9%), the utilization values obtained in the bay scallop are shown in Figure 7.

In one of the bay scallops which ventilated much less vigorously than any of the other specimens investigated, high percentage oxygen utilization values (13–72%) were found. A similar, slow, often interrupted, ventilation entailing a high oxygen utilization was observed in some individuals of Anodonta (van Dam, 1938). In the specimens of Anodonta investigated by Koch and Hers (1943; personal communication) a high utilization prevailed throughout. Whether a slow rate of ventilation, as displayed by these specimens of Pecten and Anodonta, can be considered normal, *i.e.,* will provide the animal with enough oxygen and food to sustain normal, aerobic, respiration and growth, is not known.

In the stream of water escaping from the cloacal chamber of the bay scallops considerable gradients in the concentration of oxygen occur. These gradients are shown, in Figure 7, in the form of utilization values obtained simultaneously, but at different spots, in the exhalant water current of one and the same specimen. These values were connected by a line parallel to the ordinates. The steepest oxygen concentration gradients occurred in those cases where the utilization was high. In one of these cases (the group of three dots closest to the right hand ordinate) the utilization values were 33.4%, 37.4%, and 71.5%, respectively, representing oxygen concentrations of 66.6%, 62.6%, and 28.5%, of the oxygen content of the inhaled water. In this case, then, the concentration of oxygen at one spot was more than twice as high as at another spot. In the other, more vigorously ventilating specimens, in which the utilization was much lower, the differences in oxygen concentration did not exceed 10% of the O_2-content of the inhaled water.

Inhomogeneity in the distribution of oxygen in the exhalant water current as observed in the bay scallop by the present author and in *Anodonta* by H. J. Koch and M. J. Hers (personal communication), of course, excludes the possibility of determining the true average oxygen utilization with a sampling method. Only if all the water leaving the animal could be collected would the determination of such a value be possible. The oxygen utilization values, then, obtained in this and in previous investigations, are only approximations of this average value.

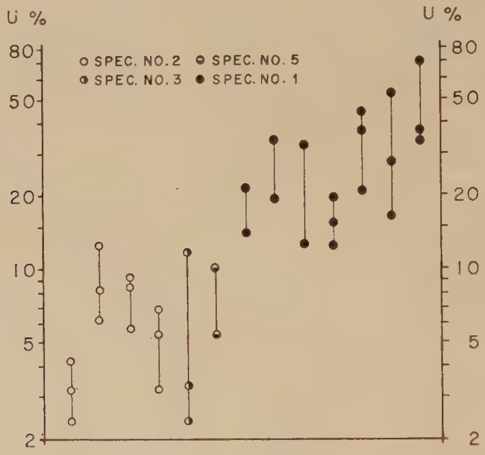

FIGURE 7. Gradients in the concentration of oxygen in the exhalant water current in the bay scallop, presented as the percentage oxygen depletion (U%) of samples drawn simultaneously at different spots in one and the same animal. U%-values from simultaneously drawn samples are connected by a line parallel to the ordinates. O_2-content inhaled water approx. 4.5–5 ml. O_2/L.; temperature about 20–24.5° C.

I wish to thank Dr. A. C. Redfield and Dr. P. F. Scholander for stimulating interest and valuable criticism, and Mr. J. A. Posgay for help in the procurement of scallops.

SUMMARY

1. The oxygen uptake and the percentage of oxygen withdrawn from the inhaled water, were determined in resting specimens of two species of lamellibranch mol-

luscs which have a capacity for rapid swimming locomotion, *viz.* in the sea scallop (*Pecten grandis* Sol.) and in the bay scallop (*Pecten irradians* Lam.).

2. In accordance with the absence of prolonged ventilation pauses common in several other species of Lamellibranchia, the oxygen uptake in the bay and sea scallop is quite uniform. In both species Q_{O_2} was found to be about 70 ml./kg./hr. at 20° C. This value is about half the Q_{O_2}-value found in swimming species from the mediterranean and falls well within the range of Q_{O_2}-values in boreal non-swimming types of lamellibranchs recorded in the literature.

3. The oxygen uptake was independent of the oxygen tension down to a concentration of oxygen of about 1-½ ml. O_2/L.

4. The percentage of oxygen withdrawn from the inhaled water, in most cases, was low, ranging, approximately, from ½ to 13%. It was demonstrated that in the stream of water escaping from the cloacal chamber of the bay scallop considerable gradients in the concentration of oxygen occur.

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Contribution No. 707

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SEA AND AIR RESOURCES*

ATHELSTAN F. SPILHAUS

THERE are three basic resources on our planet—water, air, and rock. Each contains valuable things that we can extract with power. Geophysics in its corresponding phases is the application of all basic sciences toward the understanding of the hydrosphere, atmosphere, and lithosphere. If, therefore, we ask the question, "What can geophysics contribute to the development of resources for the future?" we are really making the naive query, "How can understanding the three basic components of our planet help us to exploit them?"

Because man is essentially land-bound, two tendencies are apparent in the three geophysical divisions. First, he has divided and specialized into many parts the application of science to the best utilization of the emergent land-rock as a resource. But, secondly, he has regarded the atmosphere and the ocean as obstacles and has studied them as such, with emphasis on those vagaries in each which are to be avoided or against which he must protect himself. He has not, in general, pursued the understanding of the air and ocean as a tremendous reservoir of things that are needed for living in the future—as a vast natural resource.

Fortunately, meteorology and oceanography have not yet been broken into compartmentalized, specialized fragments, as have the sciences applied to aspects of the land-rock: we are becoming increasingly aware that in order to understand the ocean one does not study oceanography. Rather, meteorology and oceanography are the result of trained minds in the different basic sciences directing their attention to the atmosphere and the ocean.

It has been said that the water is the slave of the air; if so, it is a mutual bondage. The attack on sea and air as a resource must be made on both as a system, and not separately; neither can the influence of the land-rock on both sea and air be neglected. The interaction of air and sea is so intimate that one must understand both in order to understand either.

The chief resource of the sea is not fish, not salts, not magnesium, or any of the myriad of other valuable things that can be extracted from it—the

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greatest resource of the sea is *water*. And it is by the interaction of air and sea plus the energy of sunshine that this water is made available to us. The fresh water that reaches the land is used for certain essential purposes: to grow food; to utilize recently arrived solar energy through hydropower; and to carry off waste (including industrial and human). This last is by far the least important and should not interfere with the use of water for the other two, since all water for carrying off waste can be reprocessed and used for the main purposes.

The basic processes of evaporation from the ocean, condensation in the air, and precipitation on the land constitute the essential working of the earth's solar distillery. Yet, in spite of the importance of water, they are virtually not understood. The trouble with water as it comes naturally from the sea is that it is unsuitably distributed in time and in space, and one of the major objectives in resource research in the next 50 years should be time and space control of all phases of the natural water cycle.

Control of our environment and its resources must be man's ultimate aim in geophysics. Climate control pertains to all phases of the earth's water substance and temperature and winds (important principally as the carriers of the water substance and heat). Control of these would ultimately (1) take the weather problem out of farming; (2) make present "waste" lands available for farming and thus contribute mightily to solving the short-range (50-year) food problem; (3) make areas now inundated suitable for the raising and harvesting of foodstuffs. If the present annual world rainfall were suitably distributed in space and time, there would be ample available.

In all sciences there should be a somewhat logical sequence of stages leading to control—observation, understanding, prediction, control. We must observe before we can understand (this does not, of course, preclude a theory that forms the design of the observational phase). We must understand before we can predict. And, above all, we must be able to predict the outcome of a set of circumstances, natural or artificially induced, before we exercise control. Very often, and particularly in the social sciences, this sequence is not observed. I do not, however, wish to preach a slavish adherence to it that would preclude valuable heuristic discoveries in the latter phases that might be followed later by understanding. What I do mean is that we should lay the groundwork of observation and understanding now if we are to be able to utilize properly this resource of sea and air when we shall need it. The meteorologists, oceanographers, hydrologists, and geographers who are to attack this problem of total water control will need to be concerned about every aspect of it, not only that part of the cycle which is in the oceans and the air but the way in which controls of water are exercised by the engineers on the land surface.

The basic purpose of the rainfall part of climate control is to take water from places of excess to places of deficit and to even up the times of excess and times of deficit at any one place.

Let us take for a moment the extreme view that none of Nature's distillate which falls on land should be allowed to return to the sea before it has been used to the maximum extent. We could change the hydrologic cycle by increasing the part that returns to the sea through transpiration of plants. This would reduce the flow of rivers into the sea. Perhaps, indeed, we could eliminate the need for any flow of fresh water into the sea. This does not mean the elimination of rivers as useful waterways and aqueducts; it simply means no flow at the mouth into the sea.

Sand culture in deserts is possible if there is enough water. Natural canals (rivers) that carry water turn deserts into verdant gardens supporting teeming populations. Uniform space distribution of net water supply might be achieved by artificial canals of the scale of the Nile River and make another part of the Sahara productive by the end of this century. Though these world-scale engineering projects of future geotechnologists now appear mammoth, they loom no bigger than present-day engineering accomplishments would have appeared at the beginning of the century. It is inescapable, however, that such large projects will affect climate, and we should understand how before they are carried too far.

Natural lakes tide farmers over periods of dryness; suitable time distribution of water supply can therefore be accomplished, and is, by storage of water above the ground in artificial reservoirs or below it in natural underground basins. Should we use above-ground or underground storage? This must be determined by prediction of what the effect of manifold dams will be on climate, and also by consideration of the competing demands for the use of land.

Engineers have historically neglected the medium or environment with which they have to deal. For example, when the Wright brothers flew a machine off the ground, it was said that man had conquered the air, but not until much later was it found that the study of the atmosphere was necessary for aircraft operation. Ships have been built for centuries, yet even the most modern ones are not designed for a sea with waves in it. Speed in smooth water has been considered the criterion—a highly unnatural one.

Tracked vehicles for agriculture and wartime uses on land still bog down in some kinds of terrain, and only control of the medium of the land by soil stabilization can solve the problem. So it is that engineering control of water is going forward without the scientific knowledge of the hydrologic factors which could do so much to aid it.

I have spoken so far only of the equalizing of time and space distribution of water on the land by the obvious brute-force methods of mammoth engineering works, ultimately measured in power expended. Possibly, if a concerted attempt were made to understand the physics of precipitation, both time and space distribution of water and heat could be achieved by subtler and more sophisticated means, and with expenditure of much less power, by controlling the formation of rainfall before it hit the land.

More difficult to envisage but not inconceivable is the control of evaporation. Mulches are already used, and reforestation is attempted, though the true effects of these on evapotranspiration are not really known. Deserts occur, not necessarily where rainfall is low, but wherever evaporation exceeds rainfall and dew. Some plants have the mechanism to absorb dew at night and not transpire during the day, and they bloom in the desert –a hint perhaps at a mechanism for reducing evaporation in these areas. A corollary to water control and more even distribution would be the moderation of temperature extremes.

Just as water control will have an influence on temperatures, so temperature control will have an influence on water distribution. Temperature control may be accomplished in the future by the proper distribution of artificial or natural reflective and absorptive coverings. I have heard, for example, that dyes may be used to increase the absorption of solar radiation, and hence the evaporation in salterns. Also, the possibility exists of cutting down the reflectivity of snow and ice surfaces. These means of controlling the utilization of incoming solar radiation at the earth's surface should not be underestimated.

So far we have considered the air–ocean water resource in relation to land, but with the ocean covering more than two-thirds of the earth's surface it is well not to forget the effect of the cycle of water and other materials on the sea itself and on its products.

Of course, complete land-water conservation renders soil conservation unnecessary—if all the water returns to the sea by transpiration, soil cannot be lost except through wind erosion. On the other hand, the fertility of the sea for the production of fish might be affected by cutting off the supply of nutrients leached from land. Here again, however, it would seem that, if we understood what materials are necessary to the optimum production of ocean fish, an artificial and controlled addition of these in the right places would result in an improvement. The natural, hit-and-miss system of the rivers washing material into the sea may result in robbing the land of nutrients valuable to it but useless for raising ocean plants and fish.

It is not the purpose of this paper to do more than sketch the broad outline of the problems of future utilization of the resources of sea and air. However, the whole problem of the exploitation of ocean plant and fish life in relation to increase of human population is one that not only is important but illustrates the need of the fishery biologist-oceanographer-meteorologist-engineer-geographer team for its solution. The ultimate objective in the exploitation of the fruits of the ocean as food is also one of control.

Just as optimum farming on land involves controlled breeding, controlled feeding, controlled harvesting, and so on, so ultimately must similar controls be devised for the farming of the sea; perhaps the culmination of these is far in the future, but again the basic understanding should be laid now.

The sea is regarded by many people as a tremendous potential supplier of food, but some marine scientists believe that the potential is exaggerated. We cannot *know*, because our fishing methods are so primitive that we have little idea of the efficiency of our harvesting. There is no doubt that through a serious effort these methods could be greatly improved, but such improvement should go hand in hand with understanding efforts at selection and "domestication"—if one may employ that word for an area as vast as the world ocean.

From work now under way there are indications of an intimate relation between atmospheric processes such as winds, changes in the physical environment of the fish, and the productivity of the fish—hence the catch. Some believe, for example, that where the winds diverge and ocean water upwells, one should find the pelagic fish in great numbers. There are indications, too, that shifts in the major current systems—shifts hardly detectable by present observational methods—may cause migrations of the fish populations. These ocean-current shifts depend on changes in atmospheric circulation, and in the future a study of the weather map may tell the fisherman where to go for his optimum catch.

For long-range weather forecasting a study of the deep currents in the sea may provide a factor in prediction. In the ocean, just as for the air in the atmosphere, there is no smooth, steady solution for the transfer of cold water from higher to lower latitudes, and possibly, also as in the atmosphere, periodic pulses or outbreaks of cold bottom water effect this transfer. During these outbreaks the bottom currents may be much swifter than our present completely inadequate measurements would indicate.

What should we do now to develop the resources of air and sea? With regard to the water cycle of the atmospheric heat engine, and always with *control* as the ultimate objective:

1. We must study evaporation and evapotranspiration of plants. Plants may be useful instruments for control of evaporation, but, as with all other instruments, we must "calibrate" them in terms of the physical process we are attempting to control.
2. We must learn to understand the mechanism of nuclei in the atmosphere, both natural and artificial, and the physics of condensation and precipitation, with a view to developing artificial stimulants and inhibitors of precipitation.
3. We should consider the uses of natural polar ice as a possible source of fresh water (as suggested by John D. Isaacs) and estimate the correlated effect any large-scale effort of this kind would have on climate.
4. We should investigate methods of utilization of fog and dew.

With regard to exploring and developing the food resources in the sea, and again with control as the ultimate objective:

1. We should study fish as sensitive indicating instruments of their physical-chemical environment. Here, also, as with any other instrument, we must calibrate them in terms of the mutual influences of the ocean life and the nitrates, phosphates, oxygen, silicates, and other materials.
2. We should study the needs of the fish or plants in the ocean with a view ultimately to introducing the materials artificially.
3. We should improve fishing methods so that a controlled number, size, and so forth can be taken.
4. We should study the habits, likes, and dislikes of ocean life with the ultimate aim of artificially confining it.

How should we organize to do all this? We should build up a global network of *observation* in sea and air. We should assist institutions where scientists in many different fields may devote their combined efforts to the problem of *understanding* the ocean and the atmosphere. We should add engineers to this group to keep in mind and work out the beginnings of control.

To summarize: If the control of the sea and air and the useful things in them is kept clearly as the objective in this search, it will be an objective large enough, and with such a tremendous return, that it should attract the best scientific minds.

Contribution No. 708

NOXIOUS MARINE ANIMALS OF THE CENTRAL AND WESTERN PACIFIC OCEAN

By CHARLES J. FISH
Fishery Biologist, and
MARY CURTIS COBB
Bibliographer

RESEARCH REPORT 36

[Contribution No. 708,
Woods Hole Oceanographic Institution]
[Contribution No. 8,
Narragansett Marine Laboratory]

(NI)

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John L. Farley, *Director*

United States Department of the Interior
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Marie P. Fish provided valuable information on the ecology of noxious fishes. Dr. Leonard P. Schultz, Curator of Fishes, United States National Museum, reviewed the fish nomenclature.

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NOXIOUS MARINE ANIMALS OF THE CENTRAL AND WESTERN PACIFIC OCEAN

This report is concerned with one of several oceanic-biology subjects designated by the Navy for investigation after World War II. The objective has been to assemble, analyze, and where possible correlate with environmental factors, available information on noxious marine animals of the central and western Pacific Ocean.

Occupation of many Pacific tropical islands by military forces in World War II accentuated the threat offered by poisonous and otherwise dangerous marine animals. The central and western parts of the Pacific Ocean harbor what is probably the most varied neritic fauna to be found anywhere in the world, and this fauna includes representatives of almost all the genera known to contain inedible and venomous species. Before World War II, the number of forms identified in scientific literature as poisonous was relatively small. Japanese home waters and the Philippines seem to have received the most attention, although some poisonous species were recorded from other areas, particularly Singapore [*25*],[1] Samoa [*57*], and Hawaii [*71*]. Two restricted investigations were made in former mandated island waters. One of these is recorded in a mimeographed report prepared in 1934 by T. Yusukawa [*149*] of the South Seas Government (Japan) Research Laboratory on Contagious Diseases, at Saipan, and the other in a published report by Matsuo [*79*] of the South Seas Colonial Office (Japan), which also appeared in 1934.

According to Hiyama [*53*], the Japanese attempted no comprehensive survey of the mandated-island faunas during the prewar period, because of the widely separated habitats, the absence of laboratory facilities in the remote areas, and the existence of known edible species in adequate abundance to meet the needs of the native populations. By 1941, however, as described by Kumada [*69*]—

> Rapidly changing world situations had caused people in every walk of life in our country to realize the tremendous

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[1] Numbers in brackets throughout the report, and reference numbers in the tables, refer to numbered items in the List of References, beginning on page 37.

importance of all the natural resources available within the sphere of Greater Far-Eastern Co-prosperity, particularly the fishery resources of the Netherlands Indies, French Indo-China, Malaya, Siam, Burma, and Australian areas. Consequently, the collection and publication of information of this subject became direly needed. This, however, was not a hastily planned undertaking to meet rising demands of the time, but rather the task of compiling the results of over 30 years of painstaking investigation and study on the fishes within the boundary of Greater Far-Eastern Co-prosperity.

The first volume in a series planned to cover the western Pacific from the Antarctic to the Arctic, and sponsored by the Japanese fishery industry, was confined to the fauna of the equatorial zone. This was completed in May 1941 [*69*] and, although devoted primarily to food fishes, it contained a brief discussion of inedible species. Shortly thereafter both the Japanese Army and Navy sponsored investigations for the purpose of recording poisonous species in tropical waters under their command. One team, consisting of T. Hiyama of Tokyo Imperial University, T. Nishizawa of the South Seas Government Fishery Experiment Station, and several technical assistants, was dispatched to the mandated islands. Studies were carried out principally on Saipan and Jaluit between July and September 1941. The group returned on December 4, 1941, "just four days before the Imperial declaration of war," and in June 1942 Kumada completed an illustrated manual [*70*] with a schematic chart showing the general distribution of poisonous species (fig. 1). The same illustrations, also in color, were later incorporated in a more detailed report by Hiyama [*53*], which was issued as a special publi-

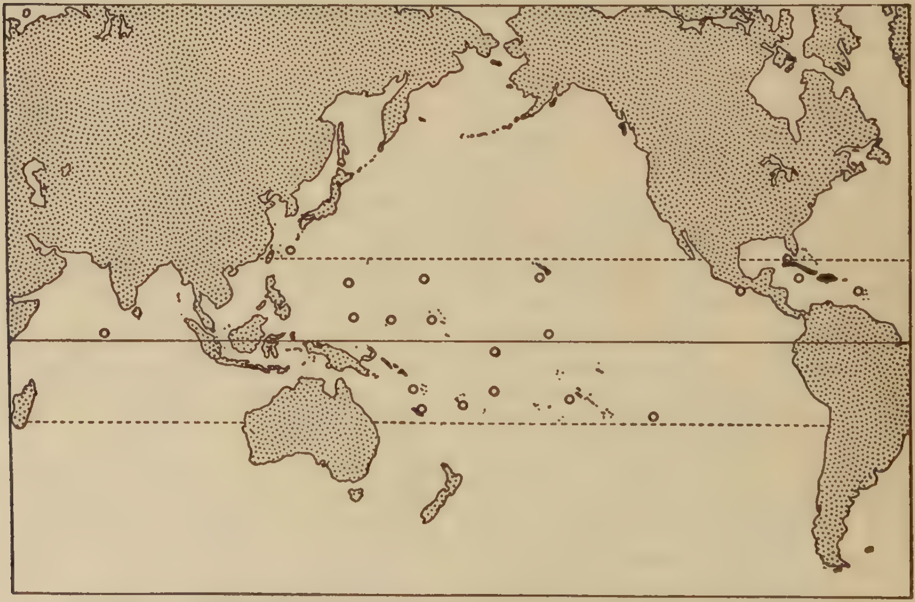

Figure 1.—Distribution of poisonous fishes (after Hiyama, 1943).

cation of the Odawara Branch of the Japanese Fishery Research Laboratory in April 1943.

A Russian report on hydrobiology by N. I. Tarasov [*134*] devotes a chapter to marine organisms dangerous to naval personnel. Brief wartime reports on dangerous marine animals were issued by the United States Army Air Forces Training Aids Division and the Tactical Center (Medical Series). The Office of Naval Intelligence, Emergency Rescue Equipment Section, and Bureau of Medicine and Surgery published similar records and manuals for the guidance of United States Navy personnel.

POISONOUS (INEDIBLE) ANIMALS

Teleosts

Almost all of the fishes reported to be poisonous in the central and western Pacific Ocean are neritic residents of the coral-reef belt (fig. 2). Within this zone relatively few of the tropical island areas have as yet been thoroughly investigated, and any species lists and distribution data compiled at this time must necessarily be far from complete. The ranges of many poisonous forms are no doubt considerably greater than existing records indicate. For example, Hiyama [*53*] found few poisonous species peculiar to the Marshalls. Most are widely distributed between Hawaii, the East Indies, and the Philippines, and belong to an Indo-Pacific fauna that according to Meyers [*88*] extends unbroken more than halfway around the world. In the Pacific this fauna ranges eastward from the coast of Asia to the Tuamotus and Hawaii, northward to Kyushu, and southward through the islands of Melanesia to the Great Barrier Reef of Australia.

Within the tropical Pacific zone there are marked regional differences. Hiyama [*53*] found that the Marshalls predominate qualitatively and quantitatively, as well as in the toxic potency of the fishes.[2] The Marianas appear to have fewer poisonous species, and their toxicity is weaker. Hiyama did not extend his observations to the Carolines, but was informed that poisonous forms are abundant about the eastern islands, and apparently absent in the western area. Jordan [*57*] found very few of 610 Samoan species poisonous, and in the Palaus [*126*] and Nauru and Ocean Island [*29*] all endemic fishes are believed edible.

Considering the central and western Pacific island region as a whole, present records indicate that perhaps 5 to 10 percent of the neritic species are on occasion poisonous. Kumada [*69*] found that, compared with 1,000 to 1,500 edible species in the "South Seas," less than 100 species are actually known to be poisonous, and Smith [*126*], after an extensive survey of former Japanese mandated islands in 1946, concluded

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[2] In Jaluit waters (Bonham Island) Matsuo [*79*] reported 36 of 180 local species inedible, but he personally identified only 23.

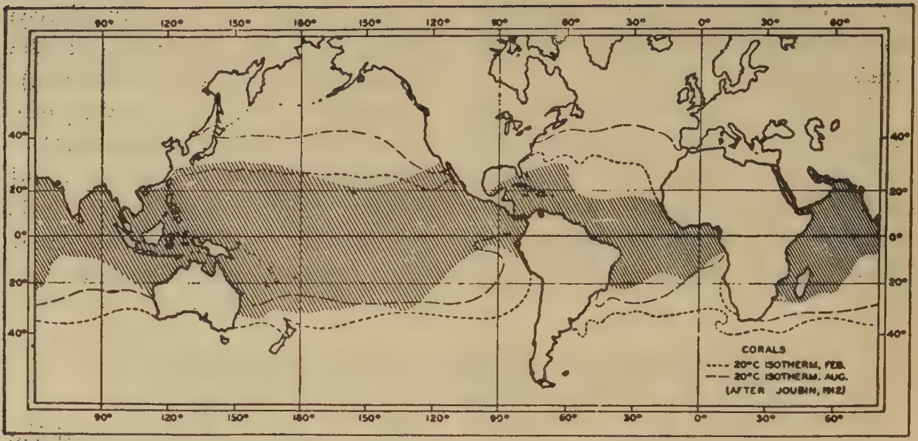

Figure 2a.—Distribution of corals (after Joubin, 1912).

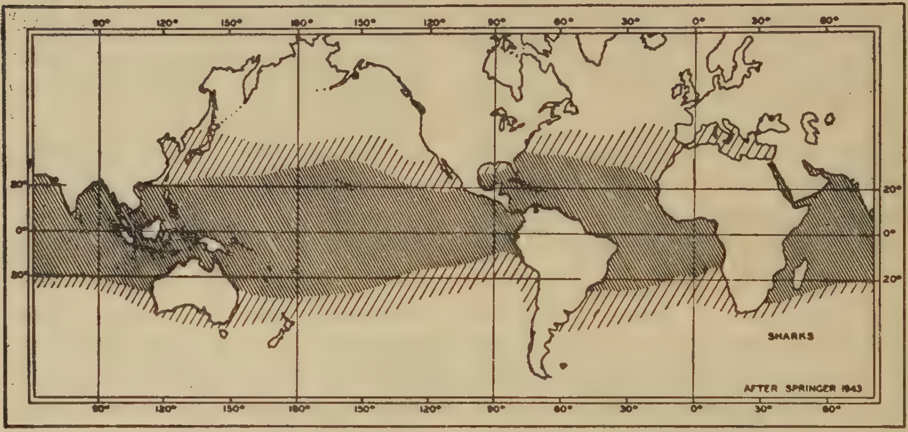

Figure 2b.—Distribution of sharks (after Springer, 1943) showing general correspondence to range of coral growth.

that about 125 of the approximately 2,000 species of fish and other marine animals in the central Pacific are considered inedible. A somewhat higher estimate was given to United States Navy officers on Saipan by an unidentified Japanese scientist who claimed to have carried on investigations for the Japanese Navy throughout the former mandated island area. He reported about 300 poisonous species in the Marshalls and 200 in the Marianas [*29*].

Although the percentage of poisonous species is usually small, individuals belonging to these species are very abundant in some localities and each year claim many victims. The Associated Press on October 6, 1947, released an account of 36 crew members of the tug *Edward M. Grimm* who became violently ill after eating fish caught in the lagoon of Palmyra atoll. One died and

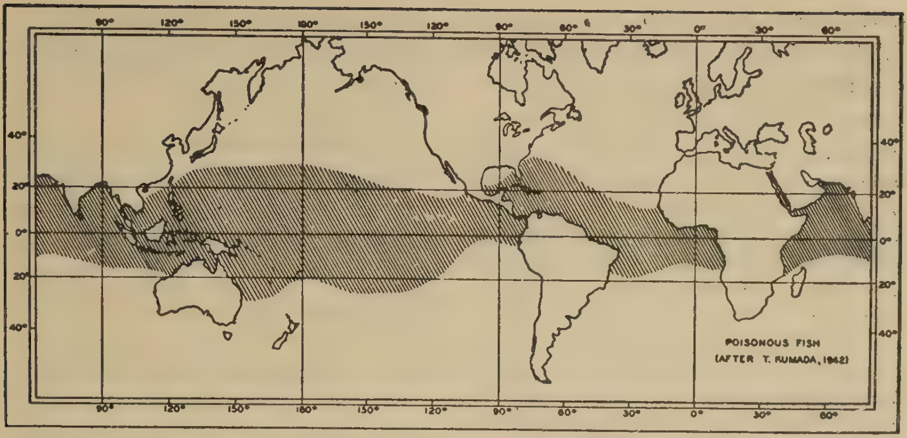
POISONOUS FISH
(AFTER T. KUMADA, 1942)

Figure 2c.—Distribution of poisonous fishes (after T. Kumada, 1942) showing general correspondence to range of coral growth.

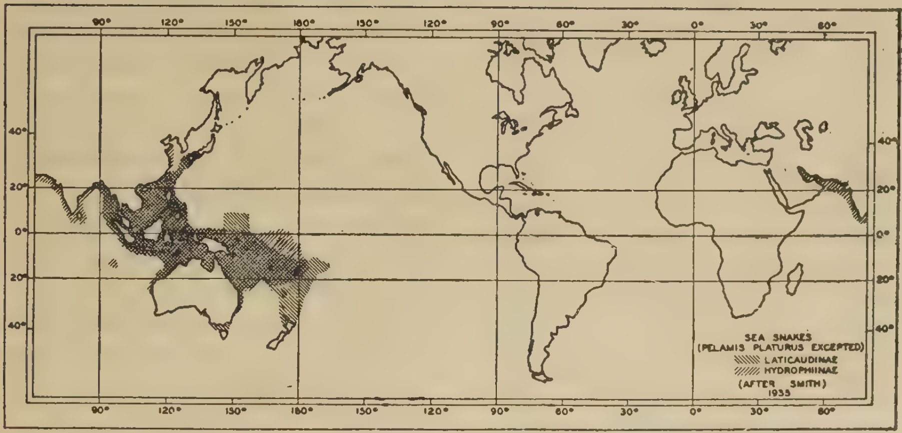
SEA SNAKES
(PELAMIS PLATURUS EXCEPTED)
▧ LATICAUDINAE
▨ HYDROPHIINAE
(AFTER SMITH)
1935

Figure 2d.—Distribution of sea snakes (*Pelamis platurus* excepted; after Smith, 1935) showing general correspondence to range of coral growth.

eight others remained in such serious condition that it was necessary to transfer them for hospitalization in Honolulu, where, according to Hiatt [*50*], cases of fish poisoning are also very common. On Fanning Island in 1946–47 there were 95 cases in a population of 224 persons, within a period of little more than a year [*116*], and on Saipan more than a score of fatalities occurred annually during the occupation of the island by the Japanese [*126*]. The Japanese placed the overall mortality from fish poisoning at from 2 to 3 percent [*29*].

The danger to humans is intensified by (*a*) frequent confusion of harmful and harmless species bearing close resemblance to each other and (*b*) conflicting evidence on species of known identity. Persons accustomed to eating certain fishes in one locality may find the same species very poisonous in another. Tybring [*137*], in 1887, made the following summation of the problem:

> Some fish seem to be poisonous at certain seasons of the year, while at others they are perfectly harmless. The spawning season seems to be the one in which they are particularly dangerous. Some fish are poisonous when caught in certain localities, while in others they may be eaten without any bad result. In most fish of this kind it is not the meat which is poisonous, but the entrails, especially the liver, the roe, and the milt; sometimes the skin also is poisonous, and finally there are some fish whose meat is poisonous. Certain kinds furnish a perfectly harmless food if eaten as soon as they are taken out of the water, but if they are allowed to lie only an hour their flesh spoils.

The latter should not properly be classed as poisonous fish since the toxin is not inherent in the living animal, and develops only when bacterial contamination occurs. "Ptomaine" poisoning of this type may result from eating many of the ordinarily edible species if they are held too long without refrigeration; in fact, according to Norman [*100*] a list of all reported poisonous species would include a large percentage of the staple food fishes in certain areas.

Misleading information is frequently received from natives who classify some species as poisonous solely on the basis of superstition and religious taboo. Kumada [*69*] encountered these age-old taboos in his investigations, and recently Capt. W. F. Jennings, Assistant Chief of Naval Operations for Island Governments, informed us that Bikini natives after arrival on Rongelap identified as poisonous several species of fishes that had frequently been eaten there by military personnel with no ill effect. It is probable that superstition is in part responsible for the Saipan natives' belief that all black fish and most red fish, as well as all fish on the outside reef, are poisonous. Among those discarded, at least one, the black-tipped sand shark (*Carcharhinus melanopterus* Quoy and Gaimard), is eaten on Guam [*126*].

In most of the fishes referred to by Tybring, the toxicity is due to an alkaloid of variable potency in their tissues. Other investigators have frequently recorded poisonous fishes of this type, including fishes whose flesh is always poisonous [*29*, *126*], those that are poisonous only at certain seasons [*29*, *42*, *100*, *151*], and those that are poisonous only in certain localities [*29*, *50*]. There are numerous reports citing species in which only certain organs are toxic [*29*, *50*, *53*, *97*, *100*, *126*, *151*]. A somewhat smaller number of species are considered edible until they reach a certain size, after which the flesh becomes poisonous [*29*, *119*].

In species showing distinct seasonal variability, there tends to be a correlation between toxic potency and gonad activity. The toxicity increases during the breeding period and is most highly concentrated in the ovaries or testes, associated viscera, and blood. Seasonal variation has not been reported in goatfishes (Mullidae) in which the poison is said to be largely localized in the brain [*50*, *97*].

The reasons for regional differences in toxic potency are a matter of considerable conjecture and must remain so until the sources of the alkaloid and the conditions favoring or inhibiting its presence are better understood. Some of the recorded cases, particularly those involving neritic forms in widely separated and climatically different areas, are obviously attributable to mistaken identity. Hiyama [*53*] lists several forms claimed by previous investigators to be edible in Japanese home waters and poisonous in the South Seas. This, he points out, is not possible, since there are no neritic species common to both areas—poisonous tropical species are not known to range north of Okinawa and Ogasawara. Confusion of this sort is less likely to occur within small areas where there are on record numerous authenticated cases of species edible in one locality and very poisonous in others nearby [*50*]. Similar variability sometimes occurs along the coast of the same island [*119*].

Regional variations in toxicity occur in both herbivores and carnivores and are frequently attributed to diet, but this has so far been difficult to prove. Hiyama [*53*] concluded that a relation exists between the nematocysts (sting cells) of coral polyps and poisonous fishes because in his field investigations he found toxic species concentrated for the most part about isolated tropical islands where clear water favors reef coral, and sparse or absent in areas of heavy terrestrial outwash not conducive to coral growth. Smith [*126*] also suggests that since surface-feeding fish taken offshore are not known to be harmful, the poison evidently originates in the food of reef and lagoon species (fig. 2). This is hardly conclusive evidence, however, because some edible fishes also feed on coral polyps, and at least one sizable Japanese jellyfish, *Rhopilema esculenta* Kishinouye, well-provided with nematocysts, is sold as a delicacy for human consumption in Nagasaki [*80*].

Norman [*100*] believes that forms like the wrasses (Labridae) and parrotfishes (Scaridae) derive their toxic properties from poisonous mussels, echinoderms, polyps, and other invertebrates which themselves contain alkaloids. A similar opinion has been expressed by Jordan [*57*], who found that, although there are no known poisonous marine foods in the Apia area of Samoa, it is reported that fishes sometimes eat poisonous deep-sea growths which appear after storms. These are said to make the flesh poisonous and sometimes kill the fishes themselves. One of the forms which becomes poisonous at times in this area is a large species of Gymnothorax known to the natives as "pusi." The fishes that poisoned many persons and domestic animals on Fanning Island in 1946–47 are said to have been nonmigratory species taken from areas in which the American Army had dumped war materials in 1945 [*116*]. The symptoms, however, appear to have been much the same as in cases of fish poisoning elsewhere. Fishermen of Saipan and Tinian believe that fishes in those waters feed on poisonous algae, but Matsuo [*79*] concluded that the alkaloids are more likely derived from echinoderms or

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crabs, although he could find no trace of any of these forms in stomach contents. Feeding experiments on Saipan proved equally inconclusive. Intestinal contents, consisting of both animal and vegetable matter, produced no symptoms of poisoning when fed to dogs [*29*].

Toxic potency increases with age in some fishes; in fact it has been reported that when young most poisonous species, if at all toxic, are only mildly so [*29*]. According to Hiyama [*53*], *Caranx sexfasciatus* becomes toxic in the Marshalls at 25 cm. (dangerously so at 50 cm.) and *C. ascensionis* at 30 cm.; in New Caledonia *Lethrinus mamlo* is said to be poisonous when larger than 80 cm. [*109*]. The barracuda, *Sphyraena barracuda*, is generally considered to be deadly poisonous in the Marshalls, although some of the other members of the genus do not become inedible until they reach large size [*53*, *119*].

Natives throughout the former mandated area use an endemic plant of the family Boraginaceae, *Messerschmidia argentea* (L. f.) Johnson, as an antidote for fish poisoning [*53*, *70*]. Known in the Marshalls as "gannato" and in Okinawa as "mampano-ki" or "hamaso-ki," *Messerschmidia* grows to a height of 6 feet along shores protected by outer coral reefs. The leaves and bark are usually decocted but are said to be equally effective when eaten raw.

FAMILIES

All families known to contain poisonous (inedible) species are believed represented in the central and western Pacific fauna, which is probably unequalled in variety and number of species elsewhere in the world. Records of 20 families, comprising 84 toxic species, have been found in the present review:

1. **Acanthuridae** (surgeonfishes). This family of herbivorous reef dwellers is represented by a large number of species, some 50 occurring in the Pacific. Of these, 6 have been reported to be mildly to moderately poisonous.

2. **Balistidae** (triggerfishes). There are at least 64 species of triggerfishes in the Pacific, of which 5, belonging to 3 genera, are known to be poisonous. Seale [*120*] has reported that in the Philippines 7 species are regarded with suspicion and that further investigation will probably reveal more. They are common about coral reefs from the East Indies to Hawaii.

3. **Carangidae** (pompanos, jacks). There are about 220 species, comprising 27 genera, in the Pacific. Of these about 75 species belong to the genus *Caranx*, the only genus reported poisonous. They abound in warm seas, often moving north in summer. Most of the species are widely distributed and are usually found near shore only in sandy protected areas. Records of but 3 poisonous species were found, and these exhibit regional and seasonal variation in toxicity [*119*] as well as toxic-potency increase with age [*53*].

4. **Chaetodontidae** (butterflyfishes). Just one of the many Pacific butterflyfishes is considered by Hiyama to be slightly poisonous. Most are brilliantly colored resi-

dents of coral-reef and volcanic-rock areas.

5. **Diodontidae** (porcupinefishes). Members of this family, like those of the related family Tetraodontidae, are generally regarded as poisonous in the tropical Pacific [*120*]. They are widely distributed sluggish fishes frequenting the bottom among weeds and coral.

6. **Engraulidae** (anchovies). The anchovies are mostly carnivorous shore fishes which congregate in schools, particularly over sandy bottom, and sometimes ascend rivers. Some 12 species belonging to 5 genera are known from Philippine waters alone. Two, including a Japanese species, have so far been reported poisonous. The Japanese species is most dangerous during the breeding season from July to September [*137*].

7. **Gempylidae** (snake mackerels). The flesh of some gempylids is reputed to be extremely purgative and oily [*51*]. One species, *Ruvettus pretiosus*, is believed responsible for 51 serious cases of fish poisoning on Saipan [*29*, *119*] although in Japan the same species is said to be valued as a food fish. The snake mackerels are mostly inhabitants of the high seas.

8. **Labridae** (wrasses). The wrasses form a very large family, being represented by at least 107 species in the Philippines alone. They are found chiefly among rocks, coral reefs, and kelp from the East Indies to Hawaii. Four species belonging to 3 genera are considered poisonous in the Pacific.

9. **Lethrinidae** (porgies). The lethrinids are important food fishes in Oceania, China, and Japan. Poisonous species appear to be confined to 2 tropical genera in which the toxic potency varies during the year and with age. Three are considered to be deadly poisonous at times [*53*]. Natives in the Marshalls believe that all members of the genus Lethrinus having "pointed mouths" are inedible.

10. **Lophiidae** (anglers). The only reference to a poisonous angler encountered in the present review is by Tybring [*137*], who reports "in China and Japan a kind of Lophius, resembling *L. setigera;* all of which are poisonous."

11. **Lutjanidae** (snappers). This is an important family of carnivores, chiefly frequenting coastlines in warm seas and comprising over 20 genera and some 250 species. Most are excellent food fishes. Just how many are dangerous is a matter of considerable uncertainty [*69*], probably because the group exhibits wide seasonal and regional variability in toxicity [*119*].

12. **Monocanthidae** (filefishes). Some 44 species (12 genera) of these small sluggish carnivores are distributed widely in the tropical Pacific. Only 2 appear to have been actually identified as poisonous [*49*, *53*], although in Philippine waters, Seale [*120*] states, 10 species are regarded with grave suspicion. The internal organs of *Alutera scripta* are deadly poisonous according to Hiyama [*53*].

13. **Mullidae** (goatfishes, surmullets). Of about 40 known species of goatfishes, 27, belonging to 3 genera, have been reported from the tropical western Pacific. Some

(N)

range northward into the temperate waters of Japan, but most are found near shore and among coral reefs in warmer climates. The flesh of all is considered edible, but in at least 2 species the brain has been found to be poisonous [*50*, *61*, *97*].

14. **Muraenidae** (morays). Hiyama [*53*] and Kumada [*70*] list 4 inedible morays, 3 of which are said to be deadly and 1 moderately poisonous. All belong to the genus Gymnothorax (p. 35) and are widespread in Oceania. Numerous other members of this genus are considered excellent food fishes.

15. **Ostraciidae** (trunkfishes). Japanese investigators have not included any trunkfishes in their lists of poisonous fishes of the former mandated areas, and Jordan [*57*] states that they are said to be always safe in Samoa. According to Schultz and Stern [*119*], however, some have been reported poisonous, and an Army Informational Bulletin [*2*] advises that "All trunk or box fishes should be avoided." This family is omitted in the following list because no poisonous species have been identified in any of the records at our disposal.

16. **Pomacentridae** (demoiselles). Only 1 of some 200 Pacific species (24 genera) of demoiselles has so far been reported poisonous, and in this species the toxic effect is said to be mild [*53*]. Most are typical small and brilliantly colored reef dwellers.

17. **Scaridae** (parrotfishes). There is but one Pacific species of this large family recorded as poisonous, and it is considered to be only mildly toxic [*53*, *70*]. At least 39 species occur in the western Pacific. All are herbivorous, and especially abundant about coral reefs.

18. **Serranidae** (sea basses, groupers). Numerous species of carnivorous serranids frequent Pacific coral reefs. Some attain large size and many are utilized for food. At least 9, belonging to 5 genera, have been reported poisonous. Some of the poisonous forms so closely resemble edible species that unfortunate incidents are common [*53*]. Reports on this group by trained investigators are also conflicting. Umali lists as market fishes in the Philippine Islands several species recorded as poisonous by others. One of these is *Variola louti* mentioned by Lee and Pang [*72*] as poisonous and by Hiyama [*53*] as violently toxic. Another, *Epinephelus merra*, according to Jordan [*57*], is often poisonous.

19. **Sphyraenidae** (barracudas). There is probably more controversy over the toxic properties of members of the single genus comprising this family than in any of the other groups. Norman and Fraser [*101*] regard all as good food fishes and attribute barracuda poisoning in the tropics to ptomaines. Umali [*138*] claims that the normally edible barracuda become poisonous after indulging in a diet of small venomous fishes, while Günther (quoted by Hiyama, [*53*]), blames species of the sardine family. There have been reports that toxicity occurs during the spawning season and that the young of some of the larger species are edible but become poisonous as they grow older [*53*, *119*]. One deadly poisonous

and one mildly poisonous species have been recorded in the former mandated area by Hiyama [*53*]. Von Fraenkel and Krick [*141*] reported cases of barracuda poisoning on Saipan, but the identity of the fish in this instance has been questioned [*29*].

20. **Tetraodontidae** (puffers, globefishes). According to Smith [*126*], only the puffers and porcupinefish seem to be universally regarded as dangerous. Numerous other observers report most tropical puffers poisonous [*49*, *57*, *71*, *119*]. In the Philippines all 14 species are so considered [*120*], and in Hawaii a territorial law prohibits the sale of a particularly potent one, *Arothron hispidus*. Nagai and Ito [*96*] estimate that in Japan about 20 people die from Tetraodon poisoning each year. It has been found that in this group the toxic properties are most concentrated in the gonads and associated viscera [*57*, *71*, *97*, *137*, *151*]. There are at least 20 poisonous species belonging to 3 genera. Not all species are toxic [*119*], however, and the flesh of some of the poisonous forms has been found edible if removed and thoroughly washed when freshly caught [*97*].

Fishes reported to be poisonous (inedible) in the central and western Pacific

[Nomenclature after Leonard P. Schultz]

Family and species	Toxicity	Distribution in central and western Pacific	Comments	Reference
Acanthuridae (surgeonfishes):				
Acanthurus bleekeri (Günther).	Moderate	East Indies, Polynesia	Tests moderately positive	*53.*
Acanthurus lineatus (Linnaeus).	do	East Indies, Philippine Islands to Polynesia.	Many cause fuguism	*57.*
Acanthurus mata Cuvier and Valenciennes.	Mild	East Indies, Polynesia		*53.*
Acanthurus olivaceus (Schneider).	do	East Indies, Micronesia, Hawaii.	Paralytic effect	*53.*
Ctenochaetus striatus (Quoy and Gaimard).	do	Tropical Pacific eastward to Hawaii.	do	*53.*
Zebrasoma veliferum (Bloch).	do	Oceania eastward to Hawaii.	Numbness of hands, face, and legs.	*53.*
Balistidae (triggerfishes):				
Balistes conspicillium (Bloch and Schneider).	Moderate	Western tropical Pacific, rarely Japan.	Paralytic effect	*53.*
Balistoides niger (Bonnaterre).	Strong	South Seas eastward to Marshall Islands, China.	do	*53.*
Pseudobalistes flavimarginatus Ruppell.	Mild	East Indies and Philippine Islands to Japan.	Considered dangerous in Philippine Islands.	*49, 53.*
Rhineacanthus aculeatus (Linnaeus).	Strong	Oceania eastward to Hawaii.	Considered especially poisonous.	*97.*
Rhineacanthus rectangulus (Bloch and Schneider).	do	do	do	*97.*
Carangidae (jacks):				
Caranx ascensionis (Osbeck).	Small: mild. Large: strong.	Oceania eastward to Hawaii, northward to Japan.		*53, 97.*
Caranx hippos (Linnaeus)	Moderate	East Indies, Oceania, tropical America.	Dangerous only at certain times and places.	*143.*
Caranx sexfasciatus Quoy and Gaimard.	Small: mild. Large: strong.	Tropical Pacific		*53.*
Chaetodontidae (butterflyfishes):				
Holacanthus diacanthus (Boddaert).	Mild	East Indies, Oceania eastward to Hawaii, northward to Japan.	Numbness of hands, face, and legs.	*53.*
Diodontidae (burrfishes):				
Dicdon holocanthus Linnaeus.	Strong	Tropical Pacific eastward to Hawaii.	Poisonous alkaloid	*50.*
Diodon hystrix Linnaeus	do	do	do	*50.*
Engraulidae (anchovies):				
Engraulis japonicus Temminck and Schlegel.	Moderate	Philippine Islands, southern Japan, Korea, China.	Most dangerous in spawning season.	*137.*
Engraulis sp	?	East Indies	Poisonous to eat	*137.*

Fishes reported to be poisonous (inedible) in the central and western Pacific—*Continued*

[Nomenclature after Leonard P. Schultz]

Family and species	Toxicity	Distribution in central and western Pacific	Comments	Reference
Gempylidae (snake mackerels):				
Ruvettus pretiosus Cocco	Variable	Tropical Pacific; Hawaii northward to Japan.	Purgative oil content	*29, 119.*
Xenogramma carinatum Waite.	Mild	Tropical Pacific, eastward to United States, northward to Japan.	do	*61.*
Labridae (wrasses):				
Cheilinus fasciatus (Bloch)	do	Tropical Pacific, East Indies, northward to Japan.	Paralytic effect	*53.*
Cheilinus sp	do	Marshall Islands	Native name "Labbo"	*126.*
Coris gaimard (Quoy and Gaimard).	Strong	Tropical Pacific, East Indies, Hawaii northward to Japan.	Paralysis. Often fatal in tropics.	*53.*
Epibulus insidiator (Pallas)	Mild	Tropical Pacific, eastward to Hawaii, northward to Japan.	Numbing of face, arms, legs	*53.*
Lethrinidae (porgies):				
Lethrinus miniatus (Bloch and Schneider).	Mild to deadly.	Oceania eastward to Hawaii.	Two forms: "Jalia," mild; "Ronet," deadly.	*53,57,109.*
Lethrinus opercularis Cuvier and Valenciennes.	Variable	South Pacific, Lord Howe Island and Norfolk Island.	Poisonous at certain seasons.	*104.*
Lethrinus sp	Mild	Marshall Islands	Native name "mameni"	*53, 126.*
Lethrinus variegatus (Cuvier and Valenciennes).	Strong	Philippine Islands, Oceania.	Paralysis, often fatal	*53.*
Monotaxis grandoculis (Forskål).	do	Tropical Pacific eastward to Hawaii.	At times fatal within 24 hours.	*53, 126.*
Lophiidae (anglers):				
Lophiomus setigerus (Wahl).	Poisonous	Japan and China coastal waters.		*137.*
Lutjanidae (snappers):				
Aprion virescens (Cuvier and Valenciennes).	Mild	Tropical Pacific, eastward to Hawaii, northward to Japan.	Paralytic effect	*53.*
Gnathodentex aureolineatus (Lacépède).	Strong	Oceania	Sometimes deadly	*53.*
Lutjanus bohar (Forskål).	Mild	East Indies, Oceania, Philippine Islands.	Numbing of face, arms, legs.	*53, 57.*
Lutjanus flavipes (Cuvier and Valenciennes).	do	Tropical Pacific	do	*53.*
Lutjanus fulviflamma (Forskål).	Moderate	do	Paralytic effect	*53.*
Lutjanus monostigma (Cuvier and Valenciennes).	do	Samoa	Produces ciguatera	*57.*
Lutjanus semicinctus (Quoy and Gaimard).	Mild	Oceania	Numbing of face, arms, legs.	*53.*
Letjanus sp	Strong	Marshall Islands	Native name "Jab." Deadly poisonous.	*53, 126.*
Letjanus vaigiensis (Quoy and Gaimard).	Mild	Western tropical Pacific	Numbing of face, arms, legs.	*53.*
Monacanthidae (filefishes):				
Alutera monoceros (Linnaeus).	Variable	Tropical Pacific, northward to China and Japan.	Said to be poisonous in Philippine Islands.	*48.*
Alutera scripta (Osbeck)	Strong	Tropical Pacific	Viscera poisonous	*48, 53.*
Mullidae (goatfishes):				
Paraupeneus chryserydros (Lacépède).	Moderate	Tropical Pacific, eastward to Hawaii.	Flesh edible, brain poisonous.	*97.*
Upeneus arge Jordan and Evermann.	do	Hawaii	Brain poisonous	*50*
Muraenidae (morays):				
Gymnothorax flavimarginatus (Rüppell).	Strong	Oceania, northward to Japan, eastward to Hawaii.	Deadly in Marshall Islands, edible in Japan.	*53.*
Gymnothorax meleagris (Shaw and Nodder).	do	Oceania, eastward to Hawaii.	Deadly in Marshall Islands.	*53.*
Gymnothorax pictus (Ahl)	Mild	Tropical Pacific, East Indies.	Poisonous at times	*53.*
Gymnothorax sp	Variable	Samoa	Native name "Pusi"	*57.*

Fishes reported to be poisonous (inedible) in the central and western Pacific—Continued

[Nomenclature after Leonard P. Schultz]

Family and species	Toxicity	Distribution in central and western Pacific	Comments	Reference
Muraenidae—Continued				
Gymnothorax undulatus (Lacépède).	Strong	Tropical Pacific, eastward to Hawaii, northward to Riukiu Island.	Deadly in Marshalls	*53.*
Pomacentridae (demoiselles):				
Abudebduf sexfasciatus (Lacépède).	Mild	Tropical Pacific	Weak toxin, sometimes harmless.	*53.*
Scaridae (parrotfishes):				
Scarus microrhinos (Bleeker).	do	Tropical Pacific, northward to Japan.	Weak toxin, Marshall Island; edible in Japan.	*53.*
Serranidae (sea basses):				
Cephalopholis argus Bloch and Schneider.	do	Tropical Pacific, northward to Okinawa, eastward to Hawaii.	Light sensory and motor paralysis	*53.*
Epinephelus fuscoguttatus (Forskål).	Strong	Oceania	Very poisonous at times	*53, 72.*
Epinephelus merra (Bloch).	Moderate	do	Often poisonous in Samoa	*57.*
Epinephelus microdon (Bleeker).	Strong	do	Total paralysis at times	*53, 126.*
Epinephelus sp	Moderate	Marshall Island		*53, 126.*
Paracanthistius oligacanthus (Bleeker).	Strong	Western tropical Pacific East Indies.	At times fatal within 24 hours.	*53.*
Plectropomus sp	Mild or harmless.	Marshall Island (Jaluit)	Native name "Jowe"	*53.*
Plectropomus truncatus (Fowler)?	Mild	Western tropical Pacific, northward to Okinawa.	Severe cases reported	*53.*
Variola louti (Forskål)	Strong	Oceania	Total paralysis at times	*53, 72.*
Sphyraenidae (barracudas):				
Sphyraena barracuda (Walbaum).	do	Tropical Pacific, northward to Japan.	Deadly in Marshalls, edible in Japan.	*53.*
Sphyraena forsteri Cuvier and Valenciennes.	Mild	Oceania	Light sensory and motor paralysis.	*53.*
Tetraodontidae (puffers):				
Canthigaster rivulatus (Temminck and Schlegel).	"Poisonous"	Japan, Hawaii	Poison in ovary	*151.*
Spheroides alboplumbeus (Richardson).	do	Japan	Viscera and gonads most poisonous.	*151.*
Spheroides chrysops (Hilgendorf).	do	do	Do.	*151.*
Spheroides hamiltoni (Richardson).	do	Oceania		*151.*
Spheroides immaculatus (Bloch and Schneider).	Strong	East Indies, New Caledonia, Philippine Islands, China, Japan.	Viscera and gonads believed poisonous.	*48, 53, 137, 151*
Spheroides oblongus (Bloch).	"Poisonous"	East Indies, Philippine Islands, Oceania, China, Japan.		*151.*
Spheroides ocellatus (Osbeck).	do	East Indies northward to China and Japan.	Ovary poisonous	*48, 57, 151*
Spheroides pardalis (Temminck and Schlegel).	do	Japan	Viscera, gonads, and blood poisonous.	*151.*
Spheroides porphyreus (Temminck and Schlegel).	do	do	Ovary poisonous	*151.*
Spheroides rubripes (Temminck and Schlegel).	do	do	Ripe ovary most poisonous.	*151.*
Spheroides sceleratus (Gmelin).	"Strong"	East Indies, northward to Japan, eastward to Tahiti.	Fatal cases in Philippine Islands.	*48, 53, 120, 137 151.*
Spheroides stictonotus (Temminck and Schlegel).	"Poisonous"	Japan		*151.*
Spheroides vermicularis (Temminck and Schlegel).	do	do	Viscera, gonads, and blood poisonous.	*151.*
Tetraodon fluviatilis Hamilton-Buchanan.	do	East Indies, Philippine Islands, Indochina.		*48, 53, 151.*
Tetraodon lacrymatus Cuvier.	do	Polynesia	Ova always poisonous	*71.*
Tetraodon lineatus Bloch	do	East Indies northward to Japan.		*151.*

Fishes reported to be poisonous (inedible) in the central and western Pacific—Continued

[Nomenclature after Leonard P. Schultz]

Family and species	Toxicity	Distribution in central and western Pacific	Comments	Reference
Tetraodontidae—Con.				
Arothron hispidus Linnaeus.	Strong	Philippine Islands, Oceania eastward to Hawaii.	Fatal cases known. Viscera poisonous.	*48, 50, 53, 97.*
Arothron meleagris Bloch and Schneider.	Mild	South Seas eastward to Hawaii.	Liver slightly poisonous	*53.*
Arothron nigropunctatus Bloch and Schneider.	do	South Seas, East Indies	Liver said to be poisonous	*53.*
Arothron reticularis Bloch and Schneider.	"Poisonous"	East Indies, Philippine Islands, Guam.		*48, 53.*
Arothron stellatus Bloch and Schneider.	Strong	East Indies to Japan, eastward to Hawaii.	Viscera very poisonous	*25, 151.*

Other forms

Attributing of regional variation in toxicity of fishes to a diet of poisonous invertebrates (pp. 7–8) is to date mere hypothesis. So far as is known, none of the invertebrate groups ordinarily selected for food by man are in themselves inedible, even though some do possess venom glands. In the case of *Strongylocentrotus drobachiensis* (Müller), an abundant northern circumpolar species of echinoderm whose viscera are considered a delicacy in certain localities, the venom discharged to narcotize prey is of such potency that fishermen's hands frequently become badly inflamed when immersed in water over the urchin beds. A. H. Clark informs us that this is not an uncommon occurrence along the Greenland coast. Further experimentation will be necessary to determine to what extent, if any, poisonous (inedible) species occur in the invertebrate phyla not used for human consumption.

DINOFLAGELLATES

Some forms, particularly mollusks and decapod crustaceans are at times rendered toxic, allegedly during the maxima of certain species of dinoflagellates. According to Bonnet and Phillips [*19*] the relation between the so-called red water (discolored by dinoflagellates) and mollusk toxicity has long been known to the Indians of California. It has also been described by numerous investigators [*84*, *85*, *86*, *87*, *127*, *128*]. In July 1927 during a period of red water near San Francisco 102 people were poisoned and 6 died after eating *Mytilus californianus* Conrad. Although outbreaks of such severity are exceedingly rare, mussel poisoning is not infrequent all along the American west coast. "Numerous communications from physicians and other persons brought out the fact that at certain parts of the coast annual occurrences of intoxications are the rule rather than the exception" [*24*].

Very little information is available from other regions. In New England there have been numerous mild cases of poisoning from lobsters (*Homarus americanus* H. Milne-Edwards) and crabs (*Callinectes sapidus* Rathbun) on two occasions since 1930, and in the Bay of Fundy paralytic shellfish poisoning is not uncommon [*83*, *95*]. All such incidents have occurred in late summer or early fall when dinoflagellates are normally in greatest abundance, but no discolored water was reported at the time of the outbreaks. There have also been very infrequent reports of mussel poisoning in at least five European countries, Germany, France, Belgium, Ireland, and Norway [*24*].

Swarms of certain dinoflagellates become so dense at times that not only is the water deeply discolored, but other marine life in the affected area is destroyed. The following possible causes for this mass mortality have been suggested by Hornell [*55*]: (1) Exhaustion of oxygen in the sea water; (2) poisoning by excretion products of living flagellates or by the products of decomposition liberated by the death of the short-living generations; (3) asphyxiation by blanketing of the fish with a mass of flagellates that have passed into the jelly-forming stage. More recently Brongersma-Sanders [*24*], after an intensive review of the available evidence, concluded that "Noxiousness of red water of dinoflagellates (probably a poison produced by the living plankton) is in my opinion the real cause of the mortality."

According to Matoda [*78*], however, observations by K. Nakazawa indicated that early larvae of mollusks and crustaceans, which breathe through the body surface, survive in discolored water, while older forms with specialized respiratory gills are killed when these organs become completely covered with the disintegrating bodies of dinoflagellates. These and similar observations by K. Oda on oysters in Gokasho Bay when *Gymnodinium mikimoti* Miyaki and Kominani swarmed in 1934, led to the conclusion that the "detrimental effect is of a physical rather than chemical nature."

Records of mass mortality of marine life have been far more frequent and widespread than reports of humans made ill by eating shellfish or crustacea. The genera involved have been identified as *Gonyaulax*, *Gymnodinium*, *Cochlodinium*, and *Noctiluca* in the sea, and *Heterocapsa* and *Glenodinium* in brackish water [*24*]. Along open coasts the maxima occur most frequently during the periods of optimum temperature in areas subject to local and periodic enrichment by nutrient-bearing waters from lower depths [*65*]. The four most important regions of upwelling are along the west coasts of continents (California, Peru-Chile, southwest Africa, and northwest Africa). In inland waters, red water and mass mortality sometimes occur owing to purely local conditions. It has been reported repeatedly in the western Pacific in bays and harbors of the Philippines [*123*], Japan [*4*, *78*, *89*, *99*], and Australia [*33*], the outbreaks tending to be more restricted in area and of shorter duration than those along open coasts.

It would appear that the danger to man lies not in the dense aggregations of dinoflagellates which quickly destroy the mollusks and crustaceans, but in the lesser maxima of poisonous species that provide toxin in quantities dangerous to humans though not lethal to other marine forms. This relation between the toxicity of mollusks and the abundance of toxic dinoflagellates is indicated by Sommer et al. [*127*] in the following comment on tests in the San Diego region:

> Perhaps if the numbers of *Gonyaulax catenella* Whedon and Kofoid and related species associated with it during the present investigation had been greater, the quantities of poison extracted from the digestive glands of the mussels might have been many times larger than the tests have indicated and the poison, possibly of sufficient potency to have caused either metabolic disturbances in the mussels or their death.

The poison in *G. catenella*, one of the dominant late-summer and early-autumn species of dinoflagellate, has been isolated and found identical with that causing mussel poisoning [*127*]. Shellfish and other cold-blooded invertebrates have a high tolerance for this poison and can assimilate comparatively large quantities without ill effect [*112*]. Man, too, appears able to resist moderate amounts, since *G. catenella* regularly occurs along certain parts of the California coast where mussels are ordinarily utilized for food.

Feeding experiments have afforded further evidence that in moderate quantity dinoflagellate toxin is not injurious to rats and humans [*1*]. However, when the assimilation in mollusks exceeds that which can be tolerated by humans, outbreaks of mussel poisoning can be expected to result. As yet there is no accurate method of determining when that critical point has been reached. The presence of red water should be considered a danger signal, but there is the possibility that in some instances critical conditions may occur before discoloration of the water can be detected. Allen [*11*] has pointed out that even experienced observers may sail through an expanse of water containing microscopic organisms in numbers of half a million to a full million per liter of sea water and detect nothing unusual. Yet the distinct red coloration may quickly appear when that number is doubled or trebled. Again, the organisms causing red water are not always toxic. On several occasions when the coloration in California waters was caused by *Prorocentrum micans* Ehrenberg, no damage to the bottom fauna was observed [*6*, *7*, *8*, *10*]. Allen has also reported several instances where the bottom fauna was undamaged during maxima of *Gonyaulax polyhedra* Stein ranging up to more than 6 million individuals per liter [*9*, *12*, *13*], although previously in the same region this species had caused great destruction on several occasions [*6*, *65*, *66*].

BLUE-GREEN ALGAE

Other than dinoflagellates, blue-green algae are the only unicellular marine organisms believed to be toxic. In the Pacific the warm-water genus *Trichodesmium* is the most frequently observed cause of discolored water on the high seas, but there is no evidence that it is injurious to other marine life except on infrequent occasions when masses are wind-driven into shallow water. At such times, mass mortality of invertebrates and fish have been reported along shore and in tide pools [*91*, *140*]. Several fresh- and brackish-water species have been proved very poisonous [*77*, *121*, *131*].

VENOMOUS ANIMALS

Venomous marine animals possess poison glands which discharge a toxic substance into wounds made by teeth or some other sharp body structure. The skin-piercing organs may be large spines of the type found on sea urchins and some fishes or the minute coelenterate nematocysts and echinoderm pedicillariae. The toxicity of the poisons produced also varies greatly in different species and may even vary in the same species in different thermal latitudes. Of the many forms having poison glands, relatively few are harmful to man. The number capable of producing serious injury and at times death is sufficient, however, to warrant the attention of anyone having occasion to enter waters frequented by species deemed dangerous.

Invertebrates

Venomous invertebrates appear to be confined for the most part to three phyla, Coelenterata, Mollusca, and Echinodermata. Representatives of these phyla abound in coastal waters throughout the world, but, as in the case of poisonous (inedible) animals, most of the dangerous species of venomous invertebrates are found in tropical or subtropical seas (fig. 2). In the few venomous species that are widely distributed in both warm and cold waters, the potency of the poison tends to increase approaching the tropics.

COELENTERATES

All coelenterates possess stinging cells or nematocysts which are used in capturing prey. The intensity of the poison varies greatly in different species, and in relatively few instances is sufficiently powerful to prove troublesome to man. In even fewer instances is it fatal. It is not possible to enumerate here all of the species whose "sting" has been claimed to be painful. Only the more commonly reported and dangerous types will be mentioned. These are largely confined to the orders Carybdeidae and Semaeostomeae of the Scyphomedusae, and the Syphonophora.

Hydrozoa. The free-swimming and attached stages in this group are usually small and harmless. In Hawaiian waters, however, the hydroid (attached) stage of one species, *Pennaria tiarella* McCrady, according to Hiatt [*50*], "causes a severe skin rash especially prevalent on midriffs from climbing onto swimming rafts offshore." In temperate American Atlantic coastal waters, where the same species is also common, the "sting" is apparently too mild to be detected by humans.

Scyphozoa. This group comprises the larger jellyfish most commonly encountered in bays and brackish waters. Few occur far from the coast or shoal offshore banks. All of the dangerous forms pass through early stages on or near the bottom, and this restricts seaward distribution. One is most likely to find them abundant within the confines of bays at definite seasons. According to Mayer [*81*] "Apart from the harbors and semibrackish estuaries one rarely finds in the tropics great swarms of medusae of a few species such as characterize the coastal waters of temperate regions."

The most deadly forms belong to the tropical order Carybdeidae, popularly known as sea-wasps. During the breeding season these medusae congregate along coasts for periods ranging from a few days to several weeks and, as pointed out by McNeill and Pope [*82*], are probably responsible for many of the fatalities attributed to the Portuguese man-of-war (p. 19). These authors report the death of a boy within 3 minutes after being stung by a sea-wasp at Darwin, Australia, in 1938. Three species, *Carybdea alata* Reynaud, *C. rastonii* Haacke, and *Chiropsalmus quadrigatus* Haeckel, have been described as dangerous in the central and western Pacific. In *C. rastonii*, the commonest species, the bell is four-sided, milky yellow, 1½ inches long, with four long pink tentacles. In the Japan Sea and Japanese Pacific coastal area it appears at the surface mainly in the early morning and evening. Its sting has been described as powerful [*52*]. Another western Pacific species, *C. alata*, is common northward to Japan where it is found in the Inland Sea during the winter season. This is a large form with a bell attaining a length of 9 inches. "The tentacles are strongly poisonous" [*52*]. *Chiropsalmus quadrigatus* has a deep transparent bell and about 28 tentacles grouped in 4 clusters. It is abundant in Philippine waters where according to Light [*75*] "the natives of Palawan reported a number of deaths caused by the sting of this medusa." Light [*74*] also cites the case of a woman severely poisoned by it in Taytay, Palawan, in 1913, and Wade [*142*] a death in September 1927 at Culion from acute jellyfish poisoning believed attributable to *C. quadrigatus.*

The most conspicuous large jellyfishes in temperate regions belong to the order Semaeostomae, some species of which also occur in the tropics. *Cyanea capillata* Eschscholtz, the only widely distributed stinging coelenterate in northern waters, commonly attains a diameter of 1 to 2 feet and may reach 7 feet in boreal-arctic regions [*46*]. In the western Pacific it is particularly abundant in summer along the coasts of Sakhalin and Hokkaido islands and in Aomori Bay [*52*]. Fisherman, who frequently contact broken tentacles coiled about their lines, develop an immunity to the sting, but the average person experiences a sharp burning sensation accompanied by inflammation which may last for hours or even days. It can be considered uncomfortable but not dangerous—no fatality has ever been recorded [*46*].

The same is true of *Dactylometra quinquecirrha* L. Agassiz, which occurs in both the tropic and the temperate Pacific. Characteristic of such forms, in the tropics the sting of *Dactylometra* is much more serious. According to Light [*75*], in October and November the Chrysaora stage of this medusa "is found in large numbers in Manila Bay where it is a menace to bathers and fishermen who hold it in great fear." It is "able to inflict a very severe and in some cases dangerous sting" [*74*]. Old [*106*] records one fatal and eight severe cases of jellyfish poisoning in Philippine waters during the period June–August in 1906 and 1907, due, Light [*74*] believes, to *D. quinquecirrha* since the only other species answering the description given is *Lobonema* whose sting is relatively mild. Another tropical member of this genus, *D. terruginaster* Kishinouye (=*D. pacifica* Göette), has "strong toxic properties" and is found along the Japanese coast from winter to early summer [*52*]. *Sanderia malayensis* Göette occurs northward to Japan where in summer it is often taken in abundance in Toyama and Amakusa bays. "Its tentacles are violently poisonous and cause much trouble among bathers" [*52*].

Also in Japanese waters, in the Seto region of Honshu, *Stephanoscyphus racemosus* Komai, a minute sessile colonial scyphomedusae, known to local fishermen as a stinging alga, according to Komai [*67*]—

> occurs in abundance in the littoral of the neighborhood and gives much annoyance to fishermen and especially to divers by causing severe pain and itch to anyone who happens to touch it with the more sensitive parts of his skin. Those who are sensitive to the poison frequently suffer from high fever for some days or weeks. The effect may come upon men who only swim in the water where the "alga" grows in abundance.

It grows on submerged objects in shallow water, usually associated with sponges (Demospongiae). A second Japanese species, *S. corniformis* Komai, occurs in greater depths [*68*].

Although less toxic than some of the Semaeostomeae, at least one genus of the order Rhizostomae inflicts painful stings. The Rhizostomae are the large jellyfishes of East Indian and other tropical Pacific seas, where they are as conspicuous as the Semaeostomeae in northern waters. Most of those frequently found swarming in bays and harbors are apparently harmless. In the Philippines, however, *Lobonema smithii* Mayer inflicts a very severe [*80*] although not dangerous sting [*74*]. Another Philippine species, *L. mayeri* Light, also inflicts a painful sting [*74*].

Siphonophora.—The Portuguese man-of-war, *Physalia*, is the most widely known and generally feared of all stinging coelenterates, but, as previously mentioned (p. 18), fatalities commonly attributed to it in the tropics are more likely to have been caused by other forms. In commenting on *Physalia physalia* var. *utriculus* La Martiniere, the common species in the warmer parts of the Indo-Pacific, McNeill and Pope [*82*] state that although attacks are not infrequent they rarely cause death. It should be avoided, however, because the pain is severe and the inflammation frequently of long duration, as evidenced by a case reported by Frachtman and McCollum [*39*]. In this instance a sailor was stung across the arms and thighs while swimming off an Oahu beach in August 1943. Over a period of 2 days the victim suffered nausea, severe abdominal and diaphragm muscle spasms, spread of clonic contractions to involve the muscles of the neck, shoulder girdle, and both upper and lower extremities, and marked difficulty in breathing. During this time the attending physicians considered the patient's condition critical. After 3 days there was general improvement, but abdominal muscle "twitching" persisted for several more days. Thirteen days after the attack he was discharged from the hospital.

Physalia is usually rather sparsely distributed over the high seas, but large concentrations are sometimes reported. One such occurrence was observed by the commanding officer of the U. S. S. *Sussex* [*139*]:

> On August 25, 1949, at 1800 G. C. T., in lat. 50°17′ N., long. 156°48′ W., we started through a great number of Portuguese men-of-war. They were visible as far, on either side, as could be seen with glasses. This sea life was observed until 1600 (ship's time) in position lat. 50°14′ N., long. 154°38′ W., a distance of about 96 miles.

Two other less conspicuous species of the siphonophore genus *Rhizophysa*, both widespread in the tropical Pacific [*63*], are known to inflict painful injury. In southern Japan, *R. filiformis* (Lamarck) "has strong attacking power—fisher-folk take care in handling seines in spring"; *R. eysenhardtii* Gegenbauer also occurs in warm waters in spring, often in large numbers [*52*].

Anthozoa.—Many of the species of both stony and naked corals inflict nettlelike stings which may leave painful red welts on the surfaces of the body, but none, so far as the records indicate, can be considered in any way dangerous [*62*, *73*]. Porites is particularly troublesome, and a species in Hawaiian waters, according to Hiatt [*50*], causes "severe rash on certain susceptible people who brush against them." Hiatt also reports that the common Hawaiian anemone, *Sagartia longa* (Verrill) "causes severe wheals and blisters on the face and neck of persons who had been squirted with fluid from its gastro-vascular cavity."

MOLLUSKS

Members of the suborder Toxoglossa (poison-tongue) have poison glands, but only one of the three families comprising the suborder are known to be injurious to humans. In the family Conidae the radula is so modified that it forms an effective biting organ by means of which venom is discharged into prey. If man is the victim, the result is serious illness or death [*27*].

All six common species of the genus *Conus* are widespread in tropical waters, and may be expected in the central and western Pacific wherever coral occurs. During the day they are most likely to be encountered on the underside of ledges or in crevices in the reefs. At night they become more active, but at best are sluggish creatures unlikely to injure anyone unless picked up or stepped on. Although the natives are well aware of the danger, and attacks are infrequent, there are numerous records of serious injury or death in which at least five of the species have been implicated. These are *Conus aulicus* Linnaeus, *C. geographicus* Linnaeus, *C. marmoreus* Linnaeus, *C. textile* Linnaeus, and *C. tulipa* Linnaeus. Cases have been reported from New Guinea, New Hebrides, New Caledonia, Tonga, Fiji, New Britain, the Carolines, and the Society, Sandwich, and Loyalty Islands [*27*, *28*, *31*, *32*, *37*, *53*, *70*, *97*].

The sixth species, *Conus striatus* Linnaeus, is not mentioned in any of the case reports reviewed, but it is a closely related species and according to Hiyama [*53*] has violent although relatively less toxic properties than other species of the genus. He lists the poison cone shells of the former mandated area in the following order of toxicity: *C. tulipa*, *C. geographicus*, *C. textile*, *C. aulicus*, and *C. striatus*. Of cases cited by Flecker [*37*] "there were two caused by *Conus aulicus* and *Conus tulipa* respectively, and these appear to be relatively mild; two instances of poisoning by *Conus textile*, one mild and the other fatal; and two of *Conus geographicus*, one perhaps mitigated by treatment by incision and the other severe." Hiyama [*53*] points out that because of the large size and beautiful coloration of the shells, collectors are the usual victims.

ECHINODERMS

Many of the echinoderms have poison glands which serve for protection, but in only a few species of the groups Echinoidea and Asteroidea is the toxic effect apparently powerful enough to be troublesome to humans.

Echinoidea.—Sea urchins occur often in large numbers and variety in shallow coastal waters. All possess spines, some very long and slender, and many if not all have poison glands associated with the spines. Any, if stepped on with bare feet, can cause painful wounds which tend to become septic, particularly in the tropics, unless all fragments of spines are removed and proper treatment received. In some a poison is discharged into sizable wounds made by the spines, but in others contact with the soft pedicellariae is sufficient. The latter have a small toothlike projection or hook at the mouth of the poison canal, and when the hooks penetrate the skin poison is discharged into the minute lesions. The most dangerous species are of the latter type and belong to the family Toxopneustidae, which according to Mortensen [*92*] "represent the climax in the development of these poison organs in Echinoids."

In the Toxopneustidae the short spines are almost completely covered by brilliantly colored pedicellariae, giving the appearance of a dense bed of small flowers. Mortensen [*92*] states:

> These "flowers" are, however, not meant to attract any animals but to warn them not to touch, as they are exceedingly

poisonous. Divers, at least in Japan where *Toxopneustes pileolus* (Lamarck) is common in shallow water, are very much afraid of them; it is stated that even death may be caused by being stung by these sea urchins.

Ohshima [*105*] has also commented on the divers' fear of *T. pileolus*, and Fujiwara [*40*] recounted his personal reactions after several pedicellariae had attached themselves to his finger:

> Instantly I felt a severe pain resembling that caused by the Cnidoblast of Coelenterata . . . After a while I experienced a faint giddiness, difficulty of respiration, paralysis of the lips, tongue and eyelids, relaxation of muscles in the limbs . . . and felt almost as if I were going to die.

The pains gradually diminished but the facial paralysis continued for about 6 hours. A second species, *T. elegans* Doderlein, is known only from Kagoshima Bay in Japan.

Some venomous members of the family Echinothuridae are large and very beautifully colored. Three species, *Asthenosoma ijimai* Yoshiwara, *A. varium* Grube, and *A. varium* var. *album* Mortensen, occur in East Indian and Malayan waters. *A. ijimai* also ranges northward to the Philippines and Japan (Sagami Bay). According to Mortensen [*94*] "The smaller spines in *Asthenosoma varium* are developed into special poison organs, carrying a single large gland, the point of the spine acting like the poison fang of a snake." However in all of the species "the strong development of the poison spines makes it quite dangerous to handle them and they are dreaded by fishermen" [*94*].

In the family Diadematidae the spines are generally very long and sharp, often exceeding a foot in length. Members of the genus *Diadema* possess poison glandular tissue but not well-developed poison sacs as in the previous group. Diademas are mainly littoral animals, especially on coral reefs and under ledges, but they may also be found frequently in the intertidal shore zone. Mortensen [*93*] says:

> To touch, not to speak of stepping upon, a Diadema is quite a dangerous matter as the very finely pointed spines sting very badly, penetrating deep into the hand or foot, the point breaking off. The pain is very intense.

Three species, all dark purple or black, are common in warm waters of the Pacific. *Diadema setosum* (Leske) and *D. savignyi* Michelin are widespread. *D. paucispinum* A. Agassiz (=*Centrechinus paucispinous* H. L. Clark) has been reported only from the Hawaiian and Laysan Islands; Hiatt states that this species "has hollow spines which carry an irritating secretion which results in a very painful wound." A related genus, *Echinothrix*, also with long sharp spines, is represented by two species, *E. calamaris* (Pallas) and *E. diadema* (Linnaeus). Both are common on coral reefs in the Indo-West Pacific north to Japan and east to Hawaii. Hiatt [*50*] also included the latter species in his note on poisonous marine animals in Hawaiian waters.

Asteroidea.—Reports of dangerously venomous starfish appear to be largely confined to members of the family Echinasteridae. Members of the genus *Echinaster* have thorny spines and aboral surface pits that secrete a poisonous fluid. This is discharged into wounds in the same manner as in the sea urchins. Another member of the same family, *Acanthaster planci* (Linnaeus), "a many-spined, multirayed starfish, has long poisonous spines on its aboral surface. The poison is paralytic and causes considerable local numbness. The species ranges throughout the Indo-Pacific to Hawaii" [*50*].

Elasmobranchs

RAYS

Stingrays have been depicted by Schultz [*118*] as "much feared demons of the sea." Certainly, because of their abundance in all warm seas and their habit of lying partly buried on the bottom in shoal water, they form a serious menace to waders.

Both the true stingrays (Dasyatidae) and the related eaglerays (Myliobatidae) have one or more spines near the base of a whiplike tail. Along the edge of the spine there is a gland that discharges poison. Some create merely painful wounds; others may prove fatal. According to Norman and Fraser [*101*] the venomous properties of the stingray have only recently been established and the mechanism explained, although they were long ago suspected by Pliny, who observed that "Nothing is more terrible than the sting that arms the tail of Trigon . . . it is as strong as iron, yet possesses venomous properties." Schultz [*118*] records several instances of severe injury resulting from encounters with Dasyatidae, the larger species of which attain a width of 5 or 6 feet.

With respect to a central and eastern Pacific species, *Dasyatis brevis*, Hildebrand [*51*] states that "These rays are considered very dangerous by the fishermen and cases are on record where they have caused severe injury, if not death, to persons hit by the stings." First-aid stations in some localities daily handle dozens of victims of another American west coast species, *Urobatis halleri* Cooper, according to Zahn [*152*], who adds that "the wound from its barbed stinger is painful, varying from an easily healing scratch of an hour's discomfort, to one that causes injury for weeks and in rare instances, death."

The eaglerays are adapted for free swimming and consequently are less likely to be encountered on shallow bottoms. For defense they rely more on escape than on the threshing of the tail [*97*]. Nevertheless, some of the species enter shoal water to feed on bottom invertebrates and if stepped on prove as dangerous as the Dasyatidae. Norman and Fraser [*101*] cite a case where the poisonous barb of the common spotted eagleray, *Aetobatus narinari*, was driven more than 2 inches into a man's leg, followed by excruciating pain. These authors mention records of many authenticated cases in which permanent disability, loss of a leg or arm, or even death, has resulted from the wound caused by the "sting." As described by Schultz [*118*]:

> Whenever stingrays occur—in the seas, bays, or in rivers—they are to be found hiding on the bottom in mud or sand. If disturbed, they swim with an undulating motion, usually close to the bottom, and stir up a cloud of mud, then come to

rest on the bottom, the muddy cloud gradually settling around the ray. This "mud cloud" and the camouflaged coloration of the fish itself, serve a definite purpose in concealing it. While thus partly buried in the sand or mud bottom, the stingray is in perfect readiness to drive its sting into any unsuspecting victim who may inadvertently step on it. The weight of a person stepping on the disk-shaped part of the body anchors the stingray, giving it the needed leverage to whip its tail upward with uncanny precision and drive the already erected spine or sting into its target. The sting, on the powerful tail of even a small ray only a foot across in size, can pass through one's foot or into the bone of the leg.

According to Norman and Fraser [*100*] there are about 30 species of stingrays. Fowler [*38*], in his report, Fishes of Oceania, records 5 genera and 12 species of Dasyatidae, and 1 species each of 2 genera of Myliobatidae. Jordan, Tanaka, and Snyder [*61*] list 6 species of Dasyatidae from Japanese waters, and Roxas and Martin [*117*] 4 species from the Philippines. R. W. Hiatt, in a letter from Honolulu, mentions 3 poisonous Hawaiian species, *Dasyatis latus*, *D. brevis*, and *Aetobatus narinari.*

Rays of the central and western Pacific

Species	Distribution in central and western Pacific	References
Dasyatidae (stingrays):		
Dasyatis akajei (Müller and Henle)	Coasts of Japan	*61.*
Dasyatis brevis (Garman)	Hawaii eastward to California and Peru	*38, 51.*
Dasyatis gerrardi (Gray)	East Indies	*38, 61.*
Dasyatis hawaiensis	Hawaii	*97.*
Dasyatis kuhlii (Müller and Henle)	East Indies, Japan	*36, 38, 61, 117.*
Dasyatis latus (Garman)	Hawaii	*38.*
Dasyatis pastinacus (Linnaeus)		*23.*
Dasyatis ponapensis (Günther)	Caroline Island	*38.*
Dasyatis sephan (Forskål)	East Indies, Micronesia	*38, 117.*
Dasyatis uarnak (Forskål)	East Indies	*38, 117.*
Dasyatis zugei (Müller and Henle)	Japan	*61.*
Pteroplatea japonica (Temminck and Schlegel)	Japan	*61.*
Pteroplatea poecilura (Shaw)	East Indies	*38.*
Taeniura atra (Macleay)	New Guinea	*38.*
Taeniura lymma (Forskål)	New Guinea, Admiralty Island	*38, 97, 117.*
Trygonoptera testaces (Müller and Henle)	Southwest Pacific	*38.*
Urolophus armatus (Müller and Henle)	New Ireland	*38.*
Urolophus fuscus (Garman)	South Japan	*61.*
Myliobatidae (eaglerays):		
Aetobatus narinari (Euphrasen)	Widespread, all warm seas	*38, 97.*
Pteromylaeus punctatus (Maklai and Macleay)	Admiralty Island	*38.*

Two other groups, the cownose rays (Rhinopteridae) and the sawfish, have been reported dangerous to humans, but there appears to be little authenticated supporting evidence. Umali [*138*], in discussing *Rhinoptera javanica* Müller and Henle, a cownose ray that occurs in large numbers in Manila Bay during its breeding season, states, "It is said that during a run of this species a fisherman from Bataan succumbed to a wound inflicted in the region of the stomach by the spine of this ray." *R. javanica* has two spines near the base of the tail. Regarding the sawfish, the same author quotes Day as reporting that in Indian waters "great injuries can be inflicted by these fishes which strike sideways with their formidable snouts." In view of the rarity of such reports, however, it is considered that the danger from these two forms is negligible.

SHARKS

Although the larger sharks depend on speed and teeth in offense and defense, some of the smaller less powerful species are equipped with venomous spines. Evans [*36*] has recently described such spines in members of three families, the spiny dogfish (Squalidae), the bullhead sharks (Heterodontidae), and the chimaeras (Chimaeridae).

In the spiny dogfish there are two dorsal spines, each with a groove containing a poison-secreting gland. The wounds are very painful and cause local inflammation which may require hospitalization. Twenty-two species of the genus *Squalus* are listed from the Indo-Australian Archipelago [*145*], one (*S. suckleyi* (Girard)) from Oceania [*38*], one (*S. fernandus* Molina) from the Philippines [*117*], and one (*S. mitsukurii*) from Japanese waters [*61*].

In the bullhead or Port Jackson sharks the dorsal spine resembles those of the dogfish, but the poison is discharged laterally. Members of the group are widespread in the western Pacific. Two species of the genus *Heterodontus*, *H. philippi* Blainville and *H. zebra* Gray, are reported from the Indo-Australian area [*145*], and one, *H. japonicus* (Duméril), from southern Japan [*61*]. Fowler [*38*] does not report them from Oceania, nor do Roxas and Martin [*117*] from Philippine waters.

The species of Chimaeridae have a movable anterior fin spine containing a gland that discharges a very virulent poison [*36*]. Seven species of the genus *Chimaera*, *C. phantasma* Jordan and Snyder, *C. mitsukurii* Dean, *C. purpurascens* Gilbert, *C. ogilbyi* Waite, *C. owstoni* Tanaka, *C. jordani* Tanaka, and *C. barbouri* Garman, are recorded from Japan [*61*]; two, *C. phantasma* and *C. deani* Smith and Radcliffe, from the Philippines [*117*]; four, *C. antarctica* Cuvier, *C. australis* Shaw, *C. callorhynchus* Linnaeus, and *C. monstrosa* Linnaeus, from Indo-Australian waters [*145*]; and one, *C. gilberti* Garman, from Oceania [*38*].

These three families of small sharks are dangerous only if handled. They do not usually frequent water of wading depth, and will not attack.

Teleosts

Any wound caused by spines or teeth of fishes, particularly in tropical waters, may become septic unless treated immediately, and it is probable that some of the species that on occasion have been reported poisonous belong to this category. This is especially true of the families Monacanthidae (filefishes) and Acanthuridae (surgeonfishes). The filefishes have sharp spines, some of which are erectile, and the surgeonfishes have one or more knifelike plates on either side of the tail, but neither group is known to possess venom glands.

FAMILIES

At least seven families of Pacific teleosts contain venomous species: Scorpaenidae (rockfishes), Siganidae (siganids), Plotosidae, Tachysuridae, Siluridae (catfishes), Batrachoididae (poison toadfishes), and Muraenidae (morays). All,

(N)

except the morays, have the poison glands associated with spines on the body surface. Morays, like snakes, eject venom from the mouth when they strike.

Scorpaenidae.—This family is represented by a large number of strikingly colored and bizarre-shaped tropical and temperate species, there being some 50 in Japan and at least 30 in Philippine waters. One venomous species, *Sebastodes joyneri*, ranges northward to Aomori Bay on the north coast of Honshu. The much-feared lionfishes, rockfishes, lumpfishes, zebrafishes, and scorpionfishes belong in this group. Most have the habit of lying motionless and partially concealed in sand or on rocky bottoms and coral reefs where their shape and coloration make detection difficult. When they are stepped on with bare feet, the venom is injected into the spine wound by pressure on the sac-like glands. In some the poison is discharged through hollow spines [*60*]. The toxicity varies in different species from relatively minor intensification of the pain in the wound to very severe pain and swelling [*97*], or even death. Hiyama [*53*] reports that a sting by *Scorpaenopsis diabolus* may prove fatal within 24 hours, and Schultz and Stern [*119*] cite the case of a boy in American Samoa who died in a few days from the sting of a tigerfish (*Pterois*).

Siganidae.—The siganids are widespread in island waters of Oceania, and at least one venomous species, *Siganus fuscescens*, is known from Japan, where it is called "aigo" [*14*, *53*]. The poison glands in this genus are associated with spines in the pelvic fins and cause painful wounds [*119*].

Nematognathoidae (Plotosidae, Tachysuridae, Siluridae).—The catfishes are represented by a very large number of species, most of which occur in fresh water. Most Pacific marine forms belong to the three above-mentioned families. One small species, *Plotosus anguillaris* (=*P. arab*, *P. ikapor*), is abundant in rivers, estuaries, and open-reef areas throughout the East Indies, and about western Pacific islands as far north as southern Japan, where it is particularly numerous in sandy bays like Nagasaki [*56*]. The structure of the poison glands in the pectoral spines has been described by Bhimachar [*17*], Pawlowsky [*108*], and Reed [*114*]. Reed found the venom to be both neurotoxic and haemalytic, and according to Alcock [*5*] a wound in the forefinger from a specimen 3 inches long made the arm numb and useless for several days even though remedies were applied without delay.

Batrachoididae.—Poison toadfishes occur in the eastern Pacific off Panama and along the South American coast, but we have found no records of them in the central and western Pacific. The most common Panama species, *Thalassophryne reticulata* Günther, is armed with four hollow opercle and dorsal spines, each with a venom gland at its base. When pressure is exerted, the venom is discharged from the tip of the spine [*56*, *119*] and causes severe pain and fever, but in no instance is it known to have proved fatal. The effect has been described as similar to that of a scorpion sting.

Muraenidae.—Morays are more generally classed as ferocious fishes, capable of inflicting severe lacerations, than as 'stingers'. In fact the literature contains conflicting opinions on their venomous qualities. According to Hiyama [*53*], "Since no poison gland has been found associated with the teeth, Gymnothorax should be, at present, considered simply a biting fish." Umali [*138*], however, in discussing *Gymnothorax pictus* states that—

> Although generally of good flavor, some morays according to Colmette, are poisonous. The poison apparatus consists of a pouch situated above the membrane of the palate, which may contain 0.5 cc of venom. The teeth are not pierced by a central canal and venom flows between them and the mucous membrane of the palate which forms a sheath.

As in the case of inedible fishes, any list of venomous species prepared at this time must necessarily be very incomplete since all are apparently neritic and relatively few Pacific Island areas have as yet been thoroughly investigated. Representative examples of the different types are given in the following table. In the warmer parts of the

Venomous fishes of the central and western Pacific

Species	Venom glands associated with—	Distribution in central and western Pacific	References
Scorpaenidae:			
Choridactylus multibarbis Richardson.	Very poisonous spines	Society Island, China	*20.*
Emmydrichthys vulcanus Jordan and Rutter.	"Stinging spines"	Tahiti	*56.*
Erosa erosa (Langsdorf)	Poisonous dorsal spines	Japan	*107.*
Hypodytes rubripinnis (Temminck and Schlegel).	Poison spines	Tokyo to Nagasaki	*56.*
Inimicus japonicus (Cuvier and Valenciennes).	Poisonous spines	China, Japan	*56,107.*
Leptosynanceia asteroblepa (Richardson).	do	Sumatra, Malacca Strait	*45.*
Minous monodactylus (Bloc and Schneider).	Extremely poisonous dorsal spines.	South Seas, China, Japan	*61,69,100.*
Pelor filamentosum Cuvier and Valenciennes.	Poison spines	East Indies and Polynesia	*56.*
Pterois radiata Cuvier and Valenciennes.	Poisonous spines	Tahiti, Society Island	*20.*
Pterois lunulata Temminck and Schlegel.	Poisonous dorsal spines	Japan, Banka Island	*107.*
Pterois volitans (Linnaeus)	Poisonous spines	Oceania, Japan	*53,97,119.*
Scorpaena neglecta Temminck and Schlegel.	Poisonous dorsal spines	Japan, China Sea	*107.*
Scorpaenopsis cirrhosa (Thunberg)	Poisonous spines	East Indies, Philippine Islands, South Japan, Hawaii.	*56.*
Scorpaenopsis diabolus (Cuvier and Valenciennes).	Violently poisonous dorsal spines.	East Indies, Oceania, South Japan Sea.	*53.*
Sebastiscus marmoratus (Cuvier and Valenciennes).	Poisonous spines	Philippine Islands, Japan, China Sea.	*107,117.*
Sebastodes joyneri (Günther)	do	Japan	*107.*
Snyderina yamanokami Jordan and Starks.	Poison spines	South Japan	*56.*
Synanceja verrucosa Block and Schneider.	Poisonous spines	Polynesia, western Pacific	*22, 97, 100, 119.*
Siganidae:			
Siganus fuscescens (Houttuyn)	do	Samoa, Palau, South Seas, Japan, Philippine Islands.	*14, 53, 119.*
Siganus puellus (Schlegel)	do	Marshall Islands, Japan	*53.*
Plotosidae:			
Plotosus anguillaris (Bloch)	Pectoral spines poisonous	East Indies, China, South Japan.	*17, 56, 108.*
Tachysuridae:			
Osteogeniosus militaris (Linnaeus)	Poisonous spines	South Seas, Borneo, Sumatra, Java.	*53.*
Siluridae:			
Parasilurus asotus (Linnaeus)	do	Japan, Korea, China	*53.*
Muraenidae:			
Gymnothorax pictus (Ahl)	Poisonous bite	South Seas, Philippine Islands, Hawaii.	*138.*

central and western Pacific, these or related species may be expected everywhere where there is suitable environment. According to Jordan [*56*], "very many genera and species of small poison fishes called 'okose' in Japan, abound in sandy bays from Tokyo southward."

Reptiles

The sea snakes (Hydrophiidae), closely allied to the cobras (Elapidae), form a specialized group adapted, both in structure and habits, for life in the sea. All are poisonous and many are deadly [*34*], but in general they will not attack without provocation. Smith [*124*], who has made an exhaustive study of these reptiles, expresses the opinion that "in their native habitat I do not believe they ever attack human beings, and the fisher-people who suffer do so by accidental contact with the creatures in the course of their work." Even so they form an everpresent danger to anyone wading in quiet waters in the tropical western Pacific. Smith found fatalities common in the Gulf of Siam, and in the Philippines Herre reported that "In most places one hears tales of death from the bites of sea-snakes" [*76*].

Hydrophiidae are generally not large; few species average more than 4 feet in length. The two largest, *Hydrophis cyanocinctus* and *H. spiralis*, average from 7 to 8 feet. Ditmars [*34*] gives 8 to 10 feet as the maximum. In color most are dark above and light below with cross-banding. The dorsal coloring may be black, purplish brown, brown, blue-gray, greenish-yellow, or yellow. The ventral side is usually yellowish-white or grayish-white although a few species are uniformly dark colored. The bands may be black, dark brown, olive, gray, or in some instances more brilliantly colored. All are readily distinguished from terrestrial forms by their paddle-shaped tails, and from the smooth-skinned eels and other eellike fishes by their rough reptilian scales.

Sea snakes are characteristically residents of sheltered along-shore waters, particularly near river mouths. Often they penetrate many miles upstream but not beyond the limits of brackish water except in the case of one species, *Hydrophis semperi* Garman, which is found in fresh-water Lake Bombon on Luzon. Another, *Laticauda crockeri* Slevin, has also become a lake dweller in Lake Tungano, 2 miles inland on Rennell Island in the Solomons, but here the water is brackish. A few of the more primitive members of the genus *Laticauda* remain semiterrestrial, but never venture far from the tide line to which they return to feed.

In calm weather, sea snakes may frequently be seen in large numbers basking at the surface They tend to collect close along shore and among corals on reefs during the breeding season, at which time they become unusually active and tend to be aggressive. In Manila Bay, fishermen frequently take as many as 100 specimens in a single beach-seine haul [*76*]. All are fish eaters and appear to hunt principally at night. More than half of the specimens taken by the Dana Expedition in the western Pacific were netted after dark when attracted by the ship's lights [*125*]. Frequently they take bait and are captured by line fishermen.

As shown in figure 2*d*, with the exception of *Pelamis platurus*, Hydrophiidae inhabit the tropical Pacific and Indian Oceans from the Persian Gulf along the Asian coast to Japan. Eastward they range through the East Indies and Oceania as far as Samoa (approximately long. 170° W.). Probably owing to the warming influence of the Kurosio current the range of at least eight species extends northward in the western Pacific to the Ryukyus, and that of four species (*Hydrophis cyanocinctus*, *Laticauda columbrina*, *Lapemis hardwickii*, and *Pelamis platurus*) to the Japanese home islands where they have been taken as far north as Kinkazan Point, Honshu [*103*]. The most northerly record is from Posieta Bay, Siberia [*98*], and probably represents a stray specimen or specimens transported into the Japan Sea in the Tusima branch of the Kurosio current.

Pelamis platurus is the only species that ventures beyond coastal waters. The most widely distributed of all the Hydrophiidae, it occurs westward across the Pacific to Lower California, Mexico, Central America, and northern South America [*34*]. It is this species that was taken in Siberian waters and the Pacific north coast of Honshu.

GENERA AND SPECIES

Smith [*124*] records 25 species from the Malayan-Philippine region, 13 in Chinese waters, and 27 in the Australian–New Guinea–Polynesian region. Fourteen genera and some 35 species in all have been reported from the central and western Pacific. These are listed alphabetically with average length, geographical range, and pertinent references in the following table.

Hydrophiidae of the central and western Pacific

Species	Length *Feet*	Distribution in the central and western Pacific	References
Acalpytophis peronii (Dumeril)	4.0	Hong Kong	*76, 124, 125.*
Aipysurus apraefrontalis Smith	1.9	Borneo, New Guinea, Philippine Islands	*124.*
Aipysurus duboisii Bavay	3.5	New Guinea	*124.*
Aipysurus eydouxi (Gray)	1.8	Cochin-China, Borneo, New Guinea, Philippine Islands.	*21, 124, 135.*
Aipysurus fuscus (Tschudi)	2.5	Celebes and Malay waters	*124.*
Aipysurus laevis Lacépède	5.6	New Guinea	*124.*
Astrotia stokesii (Gray)	5.3	Malay waters, China Sea	*124.*
Emydocephalus ijimae Stejnejer	2.8	Formosa to Ryukyu Islands	*124, 130, 132.*
Enhydrina schistosa (Daudin)	4.6	Malay waters, Cochin-China, Borneo, Celebes.	*16, 21, 45, 111, 130.*
Hydrophis belcheri (Gray)	4.0	Philippine Islands to Gilbert Islands	*124, 125.*
Hydrophis brookii (Günther)	3.4	Siam Gulf, Borneo	*21, 124.*
Hydrophis caerulescens (Shaw)	2.7	Asia coast north to China, Borneo	*16, 21, 124.*
Hydrophis cyanocinctus Daudin	6.2	Asia coast north to Idzu Sea, Philippine Islands.	*16, 21, 124, 130.*
Hydrophis fasciatus atriceps (Günther)	3.6	Siam Gulf to Philippine Islands, New Guinea.	*16, 21, 124, 130.*
Hydrophis inornatus (Gray)	2.9	Philippine Islands, China coast	*21, 124.*
Hydrophis klossi	4.2	West Siam Gulf	*21, 124, 125.*
Hydrophis melanocephalus Gray	4.0	Formosa, China coast, Ryukyu Islands	*124, 130, 132.*

Hydrophiidae of the central and western Pacific—Continued

Species	Length Feet	Distribution in the central and western Pacific	References
Hydrophis melanosoma Günther	5.1	Borneo, Macassar Strait	*21, 124.*
Hydrophis ornatus (Gray)	3.1	Asia coast north to China, New Guinea	*21, 124, 130.*
Hydrophis parviceps Smith	2.9	Cochin-China	*124, 125.*
Hydrophis semperi Garman	2.4	Freshwater lake, Luzon	*21, 76, 124.*
Hydrophis spiralis (Shaw)	6.0	Malay waters, Borneo, Celebes, Philippine Islands.	*21, 124, 125.*
Hydrophis torquatus Günther	3.4	Malay waters, Borneo, Siam Gulf	*21, 45, 124.*
Kerilia jerdoni Gray	3.1	Malay waters, Indochina, Borneo	*21, 76, 124.*
Kolpophis annandalei (Laidlaw)	3.0	Malay waters, Cochin-China	*21, 124.*
Lapemis hardwickii Gray	2.9	Asia coast to South Japan	*21, 76, 111, 124, 125.*
Laticauda columbrina (Schneider)	4.7	Oceania, Philippine Islands, Japan (Nagasaki).	*21, 124, 125, 130, 132.*
Laticauda laticaudata (Linnaeus)	4.7	Asia coast north to Ryukyu Islands, Philippine Islands, Oceania, New Guinea.	*21, 124, 130.*
Laticauda schistorhynchus (Günther)	2.9	New Guinea to South Japan	*21, 124.*
Laticauda semifasciata (Reinwardt)	4.3	Philippine Islands, Ryukyu Islands, Malay waters.	*21, 124, 130, 132.*
Microcephalophis cantoris (Günther)	6.2	Malay waters, East Indies	*21, 124.*
Microcephalophis gracilis (Shaw)	3.4	South China, Malay waters, Borneo	*21, 124, 125, 130.*
Pelamis platurus (Linnaeus)	2.9	Asia waters north to South Siberia, Japan east coast, Philippine Islands, Oceania east to United States.	*21, 34, 76, 98, 103, 124, 130, 132.*
Thalassophina viperina (Schmidt)	3.0	Malay waters to South China, Borneo	*21, 76, 124, 125, 130.*
Thalassophis anomalus Schmidt	2.7	Borneo, Sumatra, Siam Gulf	*21, 76, 124.*

SAVAGE ANIMALS

Invertebrates

No marine invertebrate can properly be classed as savage, but a few of the larger species of mollusks form a potential danger to unsuspecting divers in tropical neritic waters, particularly in coral-reef areas.

TRIDACNAS

A specimen of this common reef clam, received by the United States National Museum from Noumea, exceeds 3 feet in length and has a shell weight of 513 pounds. Equally large specimens of *Tridacna gigas* Linnaeus have also been reported from the Marshalls and Carolines [*126*]. When it is feeding, the two shell-valves remain open, but when it is disturbed they snap shut like a steel trap, and anyone unfortunate enough to insert a hand or foot would find himself firmly anchored. Even very large specimens of the giant clam are sometimes difficult to detect because the coloring and form of the soft parts blend with other reef growth and tend to conceal the shell. We have found no record of fatalities in the North Pacific, but in the South Pacific *Tridacna derasa* Bolten has been responsible for a number of deaths along the Great Barrier Reef and elsewhere, according to Yonge [*150*].

OCTOPI

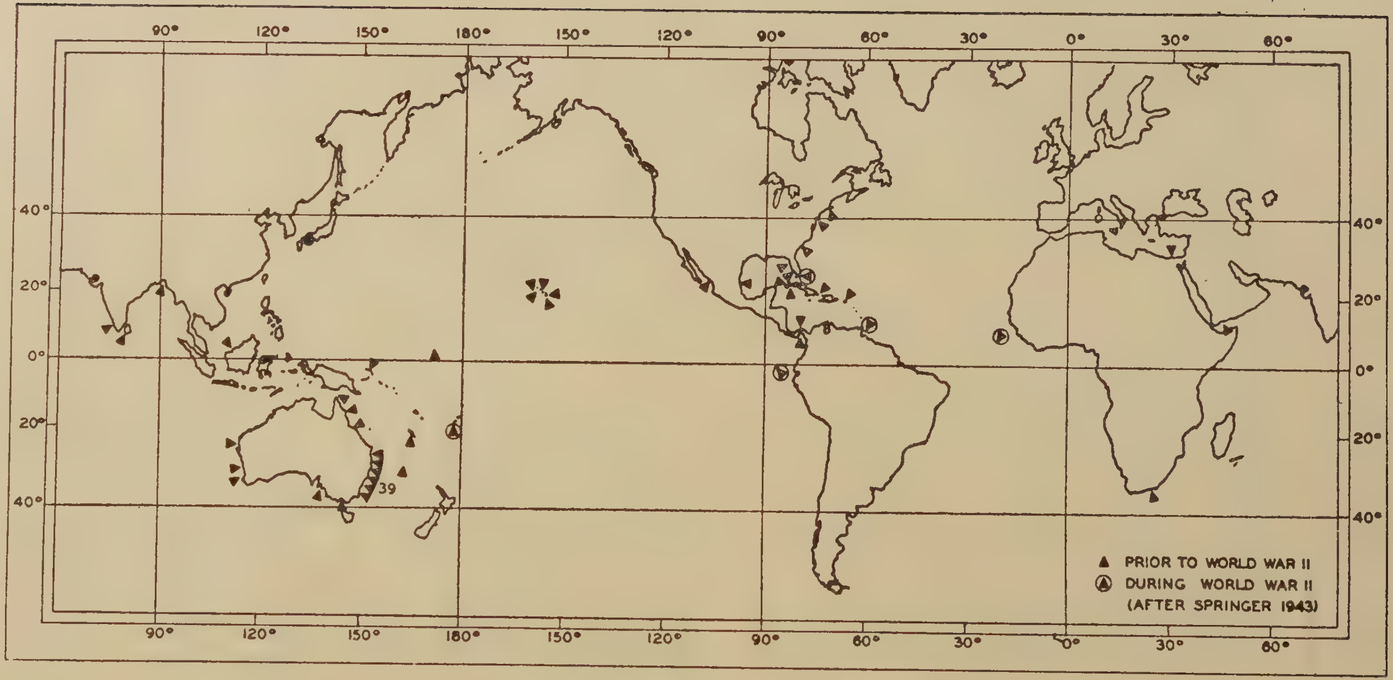
Contrary to popular belief, Pacific octopi are not considered a serious threat to divers even though some of the larger specimens may attain a tentacle spread of 28 feet [*97*]. They are rarely if ever numerous anywhere, and there is no evidence that they would attack a formidable foe without provocation. However, like Tridacna, large ones could prove dangerous to divers if disturbed. When not in motion they often pass unnoticed because of their protective coloration and their habit of lying concealed, or partly concealed, in crevices in rocks and reefs. Frequently they can be located by heaps of empty shells of food organisms at the entrances to their lairs. On inhabited atolls the stocks of both octopi and tridacnas are depleted by natives, who value them as food [*126*].

Elasmobranchs

The danger to humans from attack by sharks is a controversial subject of long standing. As recently as December 14, 1942, the Bureau of Medicine and Surgery released the following statement: "In view of the consideration noted above and in view of the Navy's experience—or lack of it—it is believed that sharks constitute a negligible danger to Navy personnel" [*26*]. Similar statements have been made by Beebe [*15*]. To refute this opinion a report, supported by a considerable number of eyewitness accounts, was issued in October 1943 by the Emergency Rescue Equipment Section of the Navy [*35*]. Of these accounts, 15 were from the Atlantic (some describing several incidents), 1 was from the eastern Pacific, 8 were from the southwestern Pacific (between October 1942 and May 1943), and 43 were from Australian waters. Numerous other authenticated cases are also on record [*2*, *64*, *101*, *102*, *110*, *113*, *136*, *148*].

The diversity of opinion appears, in large part, to have resulted from observed differences in shark behavior. It is certain that most sharks will not ordinarily attack humans. Some species, however, are unpredictable, and on occasion very dangerous. According to Springer [*129*] eight genera are known to have been implicated in attacks on man. In these animals, size is no criterion, for as Townsend [*136*] has pointed out, "A shark not so large as a man can easily mutilate and pull down a helpless swimmer without having the size to carry him away bodily." In Australian waters alone, T. C. Roughley of the Technological Museum, Sydney, reported six species considered prone to attack humans [*136*]. They are the tiger shark, hammerhead, blue pointer, great white shark, whale shark, and gray nurse shark. With the exception of the whale shark and the nurse shark, all are widespread in the tropical Pacific.

The records show that attacks occur both in deep and in shallow water; in fact a large percentage of the casualties reported by Coppleson [*30*] in Australian waters were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▲ PRIOR TO WORLD WAR II
Ⓐ DURING WORLD WAR II
(AFTER SPRINGER 1943)

Figure 3.—Incidence of shark attacks.

bathers attacked while wading, often at knee depth. They also disprove the theory that sharks will not attack if people are in groups. Both the Australian beach records and survivors' statements reveal that attacks have occurred repeatedly under those conditions and that persons with bleeding wounds are more likely to be the victims. This is understandable since sharks rely to a large extent on their olfactory organs in locating food [*129*]. In all but two of the cases in Coppleson's list, injuries included lacerations of the arms or legs, and in 13 of these only the appendages were damaged. The mortality is obviously high, approximating 80 percent in the Australian area. However, infection resulting from the bite appears to have occurred in very few instances.

Sharks of the pelagic group follow ships to feed on refuse thrown overboard, and where numerous, in certain coastal waters of the South Pacific, "they are persistent in following boats and canoes at night, nipping at the oars and paddles" [*136*]. The coastal species tend to frequent river mouths, bays, and the seaward sides of coral reefs.

Sharks may be encountered anywhere in tropical and temperate latitudes, along shore and on the high seas. Neritic ground species have relatively limited distribution and tend to remain in one locality, whereas pelagic open-ocean forms such as the dangerous maneater, the great blue shark, the tiger shark, and the common hammerhead are worldwide in warm waters. It is the latter group of powerful swimmers that is most prone to attack man.

During the summer months (principally August in the Northern Hemisphere and February in the Southern Hemisphere) some species extend their range into boreal waters, and at least one, *Somniosus pacificus* Bigelow-Schroeder, has become endemic in the Pacific Arctic. "However, records show that sharks have attacked men only in waters with temperatures ranging from 65 degrees F. upward" [*3*]. Winter and summer danger belts, assuming a critical temperature of 66.5° F., are indicated in figure 2 [*129*]. In figure 3 it will be seen that the incidents recorded by Springer [*129*] fall within this thermal range.

GENERA AND SPECIES

As relatively few of the sharks implicated in attacks have been positively identified, common members of all Pacific genera known to contain dangerous species, are listed in the following table.[3] Not all of these species are necessarily dangerous. Some, like three small East Indian relatives (*Carcharhinus melanopterus*, *C. menisorrah*, and *C. sorrah*) of the dangerous "whaler" (*C. macrurus*) of Australian waters [*30*] will probably prove to be harmless, but the distinction cannot be made with certainty on the basis of available literature.

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[3] To the original eight genera listed by Springer [*129*], *Lamna* has been added to include the porbeagle (*L. ditropis*), previously considered a member of the genus *Isurus*.

Pacific sharks reported to have been implicated in attacks on humans

Species	Common name	Distribution	References
Carcharodon carcharias (Linnaeus)	Maneater, great white shark.	All temperate and tropical seas.	*18, 30, 38, 61, 97, 101,117.*
Carcharias arenarius Ogilby	Gray nurse shark	New South Wales	*30.*
Carcharhinus commersonii Blainville	Ground or gray shark	Oceania	*38.*
Carcharhinus dussumieri (Müller and Henle).	do	East Indies to China	*117.*
Carcharhinus gangeticus (*C. japonicus*) (Muller and Henle).	do	Pacific, South Japan	*38,61,117.*
Carcharhinus limbatus (Müller and Henle).	do	Tropical and temperate Pacific.	*38.*
Carcharhinus macrurus (Ramsey and Ogilby).	Whale shark or whaler	Australian seas	*30, 129.*
Carcharhinus melanopterus (Quoy and Gaimard).	Ground or gray shark	East Indies, Hawaii, etc. (6 feet or less).	*38, 117.*
Carcharhinus menisorrah (Müller and Henle).	do	Tropical Pacific, East Indies to Japan.	*38,61,117.*
Carcharhinus munsing (Bleeker) (*C. tjutjot* Bleeker).	do	East Indies, Hawaii	*38.*
Carcharhinus sorrah (Müller and Henle)	do	East Indies to Hawaii	*38.*
Galeocerdo cuvier (Lesueur)(G. arcticus) (*G. tigrinus*).	Tiger or leopard shark	All tropical, subtropical seas	*18, 30, 38, 61.*
Hypoprion hemiodon (Müller and Henle).	Night shark	East Indies and East Pacific	*38,97,117.*
Hypoprion macloti. (Müller and Henle)	do	East Indies	*38.*
Isurus glaucus (Müller and Henle)	Maco shark	Tropical and temperate Pacific.	*38.*
Isurus mako Whitley (*Lamna mako*)	Blue pointer	Australia to New Zealand	*30.*
Lamna ditropis Hubbs and Follett	Porbeagle	North Pacific	*23.*
Prionace glauca (Linnaeus)	Great blue shark	All tropical and temperate seas.	*18, 38, 61, 97.*
Sphyrna blochii (Cuvier)	Hammerhead	East Indies, Philippine Islands, Queensland.	*117.*
Sphyrna tudes (Valenciennes)	Great hammerhead	Atlantic and Pacific	*18, 38.*
Sphyrna oceanica (Garman)	Hammerhead	Oceania	*38.*
Sphyrna zygaena (Linnaeus)	Common hammerhead	Tropical Pacific north to Tokyo.	*18, 38, 61, 117.*

Teleosts

BARRACUDAS

The barracuda (Sphyraena) is the most generally feared of all marine bony fishes, and in some parts of the Atlantic is considered a greater nuisance than the shark [*2*, *41*]. Gudger and Breder [*43*] state that, "There is little doubt that the barracuda, of all marine fish, is the one most dangerous to man." To assess its true importance is difficult since the attacker is frequently not seen by the victim, and in such cases is usually assumed to have been a shark. In the case of a United States Navy man attacked while swimming off the Coco Solo Naval Base, Breder concluded that the attack was by a barracuda, from the character of the wound [*43*]. Records of numerous other casualties attributed to barracuda are to be found in the literature. In the Pacific also, Günther [*44*] found that *Sphyraena barracuda* is extremely dangerous to bathers. There is an account [*54*] of a man attacked repeatedly, and another maimed for life by one in the well of a ship. In Java the calf muscles of a man's leg were completely torn away [*148*]. There are other instances where legs and arms have been amputated by a single bite [*119*].

Barracuda are carnivorous, pike-like fishes, mostly solitary in habit, although a California species, *S. argentea* Girard "runs in schools, some of which have been seen miles in extent" [*54*], and along the coast of eastern Australia schools of barracuda "rival those of herring and mackerel for numbers and denseness" [*144*]. However, the gregarious species are usually harmless—only the giant solitary forms are generally considered dangerous. The latter frequent tropical neritic waters and stalk their prey by remaining motionless near the surface around coral heads, wrecks, buoys, docks, and other submerged objects. In attack they dart "with a swiftness that baffles the eye" [*47*]. Gudger [*41*] describes them as "inquisitive, utterly fearless, and seemingly of implacable temper."

The genus *Sphyraena* is widely distributed throughout the world in tropical and subtropical coastal waters; some 15 species have been reported in the western Pacific. Jordan et al. [*61*] list 3 species from Japan, Fowler [*38*] 7 from Oceania, Roxas and Martin [*117*] 7 in the Philippines, and Weber and deBeaufort [*145*] 8 from the Indo-Australian Archipelago. Some are small forms, but *S. barracuda* and *S. jello* are reported to reach 8 and 10 feet, respectively, in Polynesia [*44*].

Central and western Pacific members of the genus Sphyraena

Species	References
Sphyraena agam Ruppell (S. affinis Ruppell).	*145.*
Sphyraena altipinnis Ogilby	*146.*
Sphyraena barracuda (Walbaum) (*S. picuda* Bloch and Schneider).	*117, 146.*
Sphyraena chinensis Lacépède (*S. brachygnathus* Bleeker, S. langsar Bleeker, *S. obtusata* Cuvier and Valenciennes).	*38, 117, 146.*
Sphyraena chrystaenia Klunzinger (*S. aureoflamma* Seale).	*117.*
Sphyraena ensis Jordan and Gilbert	*145.*
Sphyraena fosteri Cuvier and Valenciennes	*38, 117, 146.*
Sphyraena japonica Cuvier and Valenciennes.	*38, 61, 146.*
Sphyraena jello Cuvier and Valenciennes	*38, 61, 117, 146.*
Sphyraena nigripinnis Temminck and Schlegal.	*61, 145.*
Sphyraena pinguis Gunther	*61.*
Sphyraena genie Klunzinger	*38.*

MORAYS

These fishes are widely distributed on reefs and along shore in all tropical and south-temperate seas, but unlike sharks and barracuda they have never been reported to attack without provocation. The danger lies in their habit of lying concealed or partly concealed among rocks or in crevices in coral reefs where, if stepped on or cornered, they strike viciously. Recently, while diving in Hawaiian waters, Vernon Brock attempted to capture a large specimen which grasped his arm, inflicting lacerations so severe that hospitalization was necessary.

The number of Pacific species of Muraenidae is very large, and they range from harmless little eels to the giant *Thyrsoidea macrurus* (Bleeker), 10 feet in length [*146*]. Some members of the genus *Gymnothorax* also attain large size and are probably the most dangerous since they possess powerful jaws particularly adapted for grasping and tearing the flesh of their prey. They are also the commonest morays in most coral-reef areas. In Roxas and Martin's list of Philippine Muraenidae, of 32 species (6 genera), 20 belong to the genus Gymnothorax [*117*]. This genus also comprised 7 of the 9 species (3 genera) reported from Japan [*61*], and 20 of the 40 species (5 genera) in Weber and deBeaufort's Indo-Australian list [*146*]. One is likely to find them almost anywhere in rocky temperate and tropical shore waters and almost certainly will encounter them on coral reefs. Too little is yet known about many of the morays to permit a listing of those that could properly be designated dangerous.

OTHER SAVAGE TELEOSTS

Natives on some of the western Pacific islands claim that certain of the larger members of the grouper family attack humans [*119*], but there appear to be no authenticated cases on record. Several small species of fishes in both the North and South Pacific will also, on occasion, attack. These frequent rivers and coral reefs but cannot be considered a menace comparable to the piranha or candiru of South America. The infrequent reference to attacks of this nature would indicate also that the number of such species in the Pacific is small. Only the following three have been noted in the present review of literature.

According to Whiteley [*147*] one of the black Australian rock cods, *Epinephelus forsythi* Whiteley, "is a savage species and several of us were rushed by them as we waded on Middleton Reef and we had to beat them off." Buddle [*25*] describes two East Indian river species of puffer, *Tetraodon fluviatilis* Hamilton-Buchanan and *Spheroides oblongus* (Bloch), which, in addition to being poisonous, have a "habit of attacking bathers or fishermen wading in the sea, and inflicting a nasty bite which becomes septic. Moreover, its favorite point of attack is upon the genital organs." Both of these species are in the Philippines, Malay waters, and Indochina, and *S. oblongus* has been reported from China and Japan.

SUMMARY

Poisonous and otherwise dangerous marine animals in certain Pacific areas offer a serious problem to inexperienced personnel, and each year claim many victims.

1. Inedible and venomous forms in the central and western Pacific are for the most part neritic residents of the warm coral-reef belt (fig. 2). There appear to be few, if any, poisonous teleosts in the pelagic high-seas fauna. Savage animals occur both on the high seas and along coasts, but all recorded attacks have been in warm waters with temperatures above 65° F. (fig 3).

2. Temperate, boreal, and arctic waters are relatively free from dangerous toxic species except for occasional invasions of southern migrants during the summer months. In the few venomous forms endemic in both warm and cool climates, toxic potency tends to increase approaching the tropics.

3. Within the tropical Pacific zone it is estimated that from 5 to 10 percent of the neritic teleosts are at times inedible. Those reported to date belong to 21 families. Some exhibit marked regional, seasonal, and age variation in toxicity. Where seasonal variability occurs

there is said to be a positive correlation between toxic potency and gonad activity, but the sources of the poisonous alkaloid and conditions favoring or inhibiting its presence are not as yet understood. The Japanese have placed the overall mortality from paralytic fish poisoning at from 2 to 3 percent.

4. None of the invertebrate groups ordinarily used for food by man contain species known to be inedible, although ordinarily edible mollusks and decapod crustaceans become toxic on occasions during dinoflagellate maxima. Several species of dinoflagellates and blue-green algae have been proved toxic.

5. Venomous forms are found among the coelenterates, mollusks, echinoderms, elasmobranchs, teleosts, and sea snakes; and all except the echinoderms have caused fatalities.

6. Members of nine genera of sharks and at least four genera of teleosts have been implicated in attacks on humans in the central and western Pacific.

It is considered that the data herein presented on savage marine animals of the central and western Pacific are substantially complete, and that on venomous forms reasonably so for areas so far investigated. Information on inedible forms, however, has been derived largely from reported cases of poisoning in which there frequently has been doubt regarding the identity of the species involved and the nature of the toxicity. There is need for careful testing of all suspected species and their food organisms in different localities and at different seasons. To minimize the threat to humans, precaution should be taken in each area to determine which of the local forms are dangerous, wherein the danger lies, and where one is likely to encounter them.

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A SIMPLE METHOD FOR THE PRODUCTION OF HOMOGENEOUS WATER DROPS DOWN TO 1 MICRON RADIUS

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ABSTRACT

A simple method for the production of homogeneous water drops down to 2 μ diameter is described. When bubbles of a given size burst at an air-water interface, the collapse of the bubble cavity produces an upward moving jet which quickly disintegrates into several small drops. Each of these drops, not necessarily all the same size, rises to a height which is remarkably constant from one bubble to the next. The drop size at each of these heights was found to be equally constant.

Photographs are shown of the drops produced and their remarkable uniformity in size. The size of the drops is a function of the bubble size.

INTRODUCTION

Those who have used hypodermic needles to produce water drops of a given size for calibration purposes know only too well the difficulty involved in producing drops < about 1 mm. diameter. Surface tension considerations require that the bore diameter of the needle be many times less than that of the drop. At such small diameters high pressures are required to force the water through the bore, and, as solid materials in the water will clog the tube, the water must be filtered prior to using.

Drops down to 0.2 mm. diameter have been produced with hypodermic needles and microburets by passing a stream of air concentrically around the tip where the drops are being produced (1, 2). In the presence of the air stream the drops are blown free at a diameter far less than they would have in the absence of the air stream. However, even these techniques are inadequate to produce drops <100 μ diameter. The production of homogeneous clouds of drops <100 μ has been accomplished by utilizing the centrifugal forces associated with water on spinning discs. With an apparatus utilizing this principle, Walton and Prewett (3) produced monodisperse clouds from 15 μ to 3 mm. diameter. An improved model was capable of extending the lower limit to 6 μ (4). An entirely different method for the production of a monodisperse cloud, recently discussed by Vonnegut and Neubauer (5), produces streams of electrified uniform drops of about 0.1 mm. diameter by applying potentials of 5–10 kv. (a.c. or d.c.) to liquids in small capillaries. Under some conditions a smoke of particles of about 1 μ diameter can be produced. Drozin (10) has extended these electrical studies.

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The present paper will describe a simple method for the production of homogeneous drops from about 500 down to at least 2 μ diameter. The experimental setup requires simply a stream of bubbles rising in a beaker of water. The realization that uniform drops could be systematically produced with such a simple apparatus came out of a photographic study (6) of the mechanism of the bursting of bubbles at an air-water interface (7). High-speed photographs conclusively showed that upon the collapse of a bubble a narrow jet rises rapidly from the bottom of the bubble cavity. Within a distance of perhaps one bubble diameter the jet proceeds to break up into five or six drops, all of which rise to characteristic heights. With the same bubble size these heights are systematically obtained, thus indicating the reproducibility of the various drop sizes at different levels.

These phenomena have been studied, in connection with different problems, by other investigators. Stuhlman (7) was interested in the problem of effervescence and was the first to suggest the jet mechanism as being responsible for the production of drops from breaking bubbles. Boyce (8), in connection with studies of the deposition of airborne salt particles on coastal plants, obtained data for the average diameter of drops ejected by bubbles in sea water as a function of bubble size. However, as neither Stuhlman nor Boyce studied the breaking bubble mechanism as a source of homogeneous drops, it was felt worth while to present the ideas contained in this paper.

Experimental Methods

The production of a steady stream of uniform bubbles of any diameter $>50\ \mu$ is easily accomplished by forcing air through fine tips produced by drawing out a length of glass capillary tubing. The size of the bubble is, of course, a function of the bore diameter. The smallest bubbles are produced from hairlike tips with an air pressure of approximately 30 p.s.i.

If the bubbles are allowed to rise in distilled water, they will break immediately on contact with the surface, providing the surface is clean. It is sometimes necessary to have the glass capillary tip near the surface to prevent the coalescence of bubbles as they rise through the water. However, if both these precautions are observed, a uniform and systematic breaking of the bubbles will occur. As each bubble breaks, the upward moving high velocity jet will form and break into a series of droplets. These droplets rise at speeds, estimated both from analysis of high-speed photographs and by computation, of several hundreds of cm. sec.$^{-1}$. The frictional retarding

FIG. 1*a*. A photograph, taken at an exposure of 0.01 sec., of the homogeneous drops produced by the breaking of bubbles of approximately 450 μ diameter. The length of the streaks is a function of the fall velocity of the drops and this is directly related to the drop diameter. The water surface is slightly beneath the bottom of the photograph (see Fig. 1*b*). The vertical streak in the lower left center represents a drop moving rapidly upward from the bubble cavity.

force at such high speeds causes a rapid deceleration and loss of kinetic energy of the drops. For a given bubble diameter each of the drops will rise to a height which is remarkedly reproducible. If a slow drift of air exists over the water surface, the drops will fall at an angle to the vertical. This is illustrated in the photograph of Fig. 1*a*, where the bubbles are breaking in rapid succession so that six or more drops from the highest trajectory are simultaneously air-borne. This photograph was made at 0.01 sec. exposure with the aid of forward scattered light. With smaller bubbles and a higher rate of production one is able to produce drops at such a rate that 30 or more of the drops from the top trajectory are air-borne simultaneously.[2] This simple experiment, with the great uniformity of the settling rates of the drops formed, soon convinces one of the homogeneity of the drop diameters.

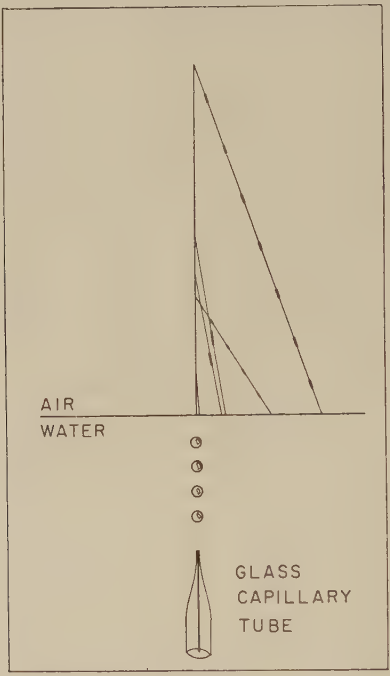

FIG. 1*b*. A drawing based on Fig. 1*a* to show the most probable trajectories of the drops. The heavy dashed lines represent the drops as shown in 1*a*, while the light solid lines indicate the trajectories.

RESULTS

Figure 1*b* is a drawing, based on the photograph of Fig. 1*a*, to show the most probable trajectories of the drops. Note that the second and third trajectories from the top are represented in the actual photograph by single drops. These drops are sufficiently large and fall back to the surface at such a rate as to prevent more than one drop for each trajectory from being air-borne at any one time. The lowest trajectory on the drawing represents a fifth drop which did not happen to be air-borne during the brief exposure for the photograph. This drop is the largest of all the drops and even on its downward flight is discernible to the eye only as a streak of light.

[2] These drops are usually invisible to the unaided eye in normal daylight. They are best made visible by viewing against a black background and looking at an angle of about 140° as measured along a strong beam of light.

A crude estimate of the drop sizes represented by Fig. 1*a* can be obtained with a knowledge of their fall velocities and Stokes' law. The fall velocities were obtained by measuring the vertical component of the streaks, which represents the drops motion during the exposure, and dividing by the exposure time. With the fall velocities of the drops from the four different trajectories thus obtained, Stokes' law can be used, starting with the top trajectory, to obtain drop diameters of about 60, 75, 70, and 40 μ, respectively.

These diameter calculations have been mentioned only to indicate roughly the range of droplet sizes produced by a breaking bubble of the size used in the illustration (approx. 450 μ diam.). However, it might be well, for this and any future experiments, to qualify the use of Stokes' law. In the first place significant errors can be obtained with Stokes' law when it is applied to drops above about 70 μ diameter. With a diameter of 70 μ Stokes' law will give a fall velocity some 5% in excess of that actually obtained. Secondly, in the present case, one must assume that there is no effect on the fall velocity by updrafts created by the bursting bubbles. Although an updraft exists in a region within a few bubble diameters of the axis of the jet, its effect on the drop is negligible if a slight horizontal drift of the air serves to carry the drops far outside the updraft region (see Fig. 1*a*). In these regions the absence of any pronounced microturbulence in the air structure due to the jet updraft is indicated by the uniform settling velocities of the drops. It goes without saying that greater over-all accuracy is obtained in the foregoing considerations if evaporation of the drops in their trajectory is eliminated by enclosing the area and allowing the vapor pressure of the air to come into equilibrium with that of the water surface. Indeed, the writer has found this imperative for the study of small drops.

The homogeneity of the drops produced by the top trajectory of Fig. 1*a* is illustrated by Fig. 2. This is a photograph of the imprints of the drops on an ammonium chloride coated slide. The diameter of the imprints shown in Fig. 2 was several times the diameter of the drops. This is probably explained by the high solubility of NH_4Cl in water. Nevertheless, regardless of the ratio between the diameter of the imprints and the drops, the uniformity of the imprints testifies to the remarkable uniformity of the drop size from the top trajectory. The other trajectories produce their own uniform drops, but the upper one, being more readily accessible, was preferred as the source of uniform drops in the present study.

The drop diameters and the heights to which they are ejected is a function of bubble size and is dependent on whether the bubbles are breaking in sea or distilled water. Figure 3 is a graph of bubble size vs. the heights of the ejected drops. The solid lines are the results of measurements in distilled water by Stuhlman (7), who found six drops produced by the majority of bubbles. The dashed line represents some recent measurements of Boyce (8) in sea water. Note that he was concerned only with the top drop. A maximum ejected height is found in each case, with the drops from bubbles in sea water rising higher (for bubbles $>800\ \mu$) and reaching a maximum height at a greater bubble diameter than the same bubbles in distilled water.

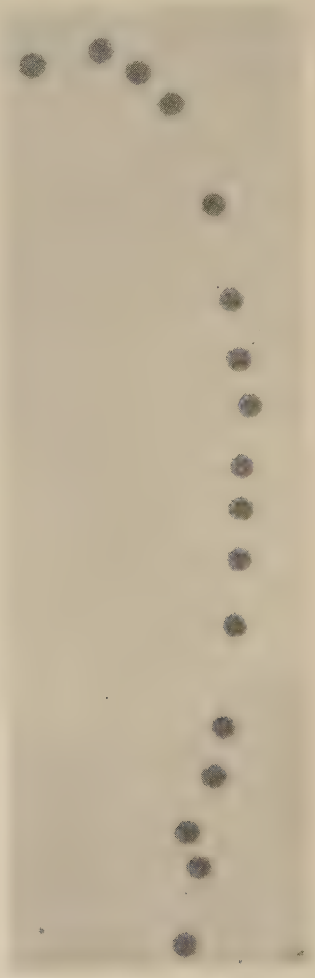

FIG. 2. Imprints of drops on an ammonium chloride coated slide. These drops represent those ejected to the greatest height when bubbles of 450 μ diameter break at an air-water interface. (See the top trajectory of Fig. 1*a* and 1*b*.)

Boyce (8) has presented experimental data on the diameters of the highest drop ejected by bursting bubbles in sea water as a function of bubble size. The data fit the linear equation $y = 51.5x - 3.95$ where x is the bubble diameter in millimeters and y is the drop diameter in microns. The data,

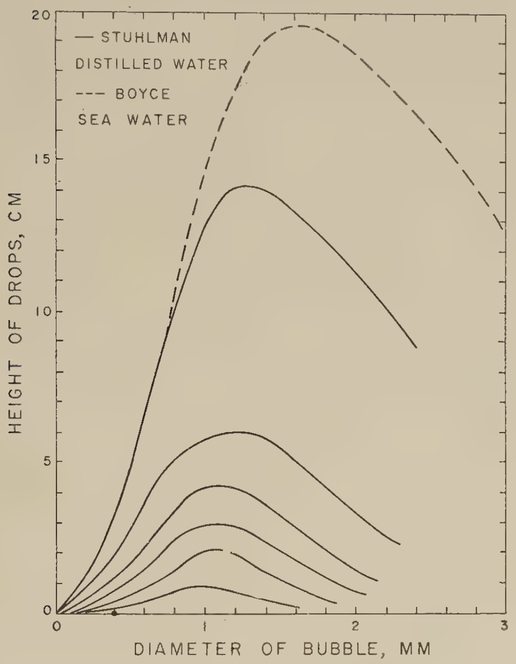

FIG. 3. The height of ejection of drops from breaking bubbles as a function of the bubble diameter. The solid lines were obtained by Stuhlman (7), who observed six drops produced when a bubble breaks in distilled water, and the single dashed line was obtained by Boyce (8). This latter measurement is for the maximum ejected height for drops produced by bubbles breaking in sea water.

however, represent the drop diameter at 83 % relative humidity and 21° C. To obtain the diameter when ejected from the bursting bubble one would have to compute the equilibrium size at the temperature and relative humidity (98 %) existing over the sea water at the time of ejection. These computations are easily done with the aid of graphs relating density, temperature, and saturation vapor pressure with chlorinity of the water (9). The above equation, although probably correct for large bubbles, cannot possibly hold for bubbles $<77\ \mu$ diameter, for below this size the equation predicts negative droplet diameters. Inasmuch as the writer has obtained droplets between 2 and 10 μ diameter from bubbles $<77\ \mu$, and as Boyce seemed little concerned with the small bubbles, it is justifiable to limit consideration of this equation to the larger bubbles.

In order to insure a continuous and rapid rate of production of homogeneous drops it is necessary, as was mentioned earlier, to maintain a clean water surface. This becomes more critical as the bubble diameter increases and especially so in the case of bubbling in sea water. Little difficulty is experienced, however, if the bubbles are < about 600 μ and preferably breaking in distilled water. Fortunately, it is the smaller bubbles that are producing the drops in the size range that are beyond the limits of hypodermic needles, and it is in this size range that the bubble technique produces homogeneous drops with a high degree of accuracy.

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Contribution No. 713

Särtryck ur Tellus nr 3, 1954

Serial Observations of Drift Currents in the Central North Atlantic Ocean[1]

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(Manuscript received May 13, 1954)

1. Introduction

Between October 21, 1953 and February 9, 1954 a series of nearly continuous observations of wind-drift currents was made in the open ocean off Bermuda by means of drifting wireless-telemetering buoys. A rough plot of the position of each of these buoys relative to Bermuda was obtained by means of a mobile radio-direction-finding station. A composite plot of the tracks of all the buoys is exhibited in Figure 1. The island provides such a small base line for triangulation, especially for bearings to the northeast and southwest of the island, that reliable fixes of position could be obtained only during the time that the buoys were within about 20 miles of Bermuda. Because of the uncertainties in radio-direction-finding at 3 megacycles the information shown in Figure 1 cannot be used for measuring wind-drift of the buoys, but it does provide us with enough information to eliminate from the data those cases in which the buoys were within the 1000 fathom line. A total of 65 days of observations satisfying this criterion was obtained.

Figure 2 is a sketch of the buoy. A cylindrical steel can roughly 2 feet in diameter and 5 feet high surmounted by a 6 foot mast (which carried a 4 cup anemometer, wind vane, magnetic compass and whip type antenna) and carrying a 30 watt radio transmitter, telemetering equipment and batteries, is ballasted so as to float with about 5 inches of freeboard. To the lower portion of the can are attached two outrigger arms, from one of which is suspended a sheet metal drogue at depths from 120 to 530 feet. On the other arm a sheet metal rotor (Figure 3) is suspended as near to the surface as possible. Every three hours (in some cases every $1^1/_2$ hours) the buoy transmits by wireless the following data: (i) the number of revolutions of the rotor since the previous transmission; (ii) the number of revolutions of the anemometer since the previous transmission: (iii) the instantaneous magnetic heading of the buoy; (iv) the instantaneous bearing of the wind relative to the buoy. These wireless signals turn on the magnetic tape recording equipment in the land-based observatory so that the data is available for reduction in recorded form. The operation of the receiving station is entirely automatic except for occasional changing of reels of recording tape. The system in use at present works satisfactorily over distances up to 45 miles. Rough weather, even of moderate gale force, does not harm the buoys.

Calibration of the rotors was carried out in a tidal channel on the island. Because the buoys are free drifting they do not measure

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[1] Contribution No. 713 from the Woods Hole Oceanographic Institution; under Contract with the Office of Naval Research. The work was done at the Bermuda Biological Station.

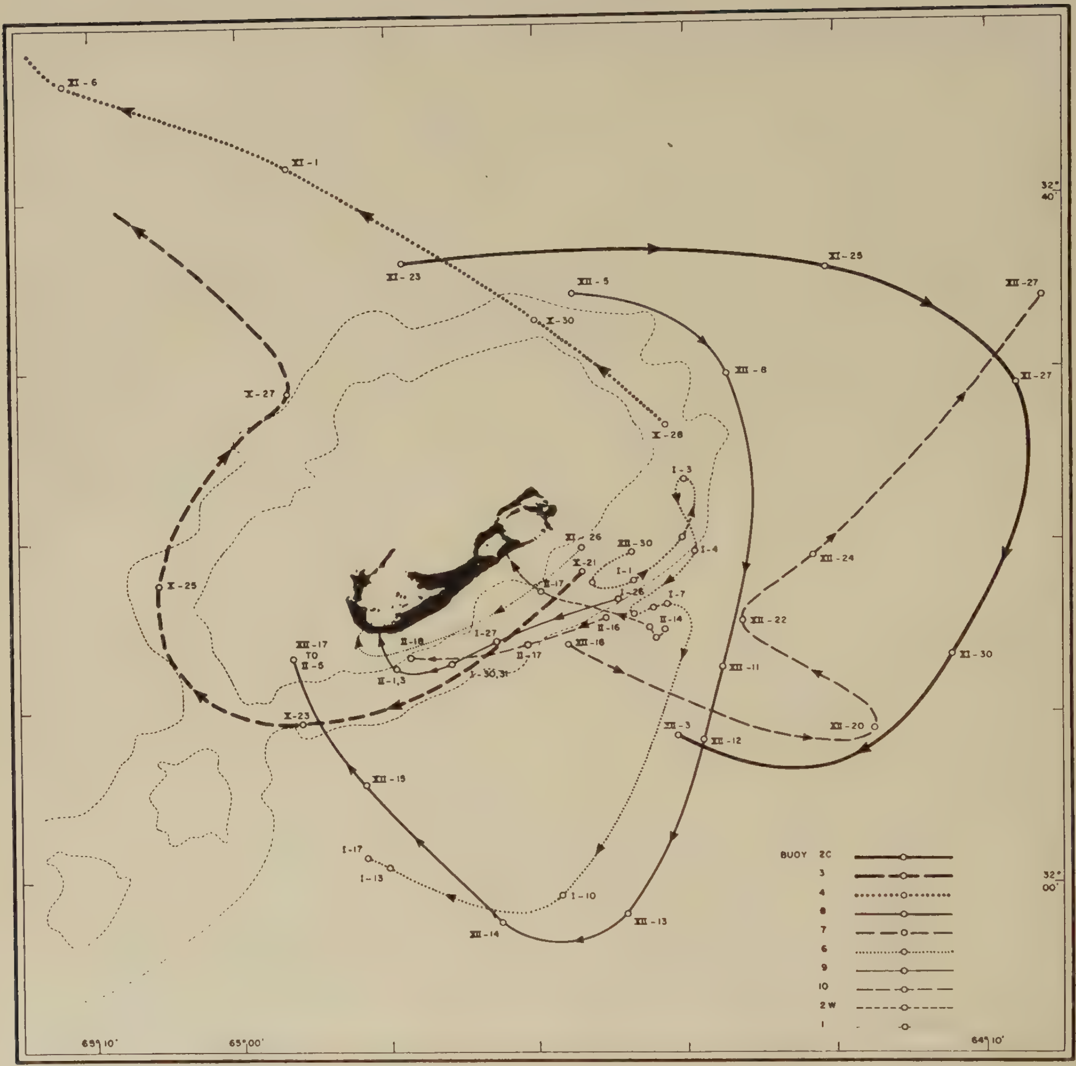
XI-6
XI-1
XI-23
XI-25
XII-5
X-30
XII-27
XII-8
XI-27
X-27
X-28
I-3
XI-26
XII-30
I-4
X-21
I-1
XII-24
I-26
I-7
X-25
II-14
II-16
XII-22
XII-17 TO II-5
II-18
I-27
XII-18
II-17
XI-30
II-1,3
I-30,31
XII-11
X-23
XII-3
XII-12
XII-20
XII-15
I-17
I-13
I-10
XII-13
XII-14
BUOY
2C
3
4
8
7
6
9
10
2W
1
32° 40'
32° 00'
65° 10'
65° 00'
64° 10'

Fig. 1. Tracks of the various buoys around Bermuda. Contours of the 100 and 1000 fathom lines are drawn in about the island. The tracks of different buoys are shown by different qualities of line. The Roman numerals indicate the month and the numbers immediately following them the day. Tracks ending in shallow water show buoys that came ashore. Tracks pointing off the chart indicate buoys which drifted out of radio-direction-finding range but which were still able to telemeter data properly.

the velocity of the surface drift relative to the ocean bottom. They measure the vectorial difference of the surface velocity and the velocity at the depth of the drogue. The areas of the can and rotor together (in the surface water) and of the drogue (in the deep water) are nearly equal so that the actual speed of the vectorial difference is twice the speed past the surface rotor. The orientation of the buoy is determined by the direction of the vectorial difference. In this connection every effort has been made to reduce the area exposed to the wind. There is a small deflection (averaging 10°) of the orientation of the buoy from the direction of the vectorial difference of surface and deep velocities, due to Magnus effect of the rotor. A correction for this has been made on the basis of experiments made in a tidal

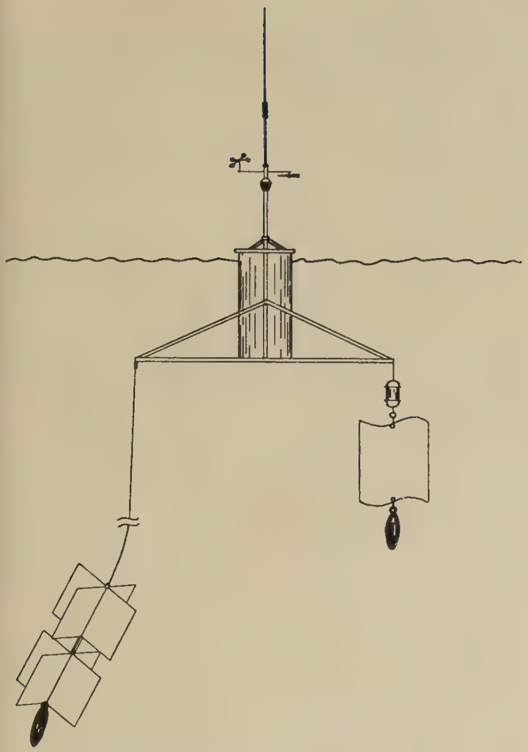

Fig. 2. Schematic sketch of the buoy showing the radio mast and meteorological instruments above water, the current and the deep drag each attached to ends of the outrigger arms.

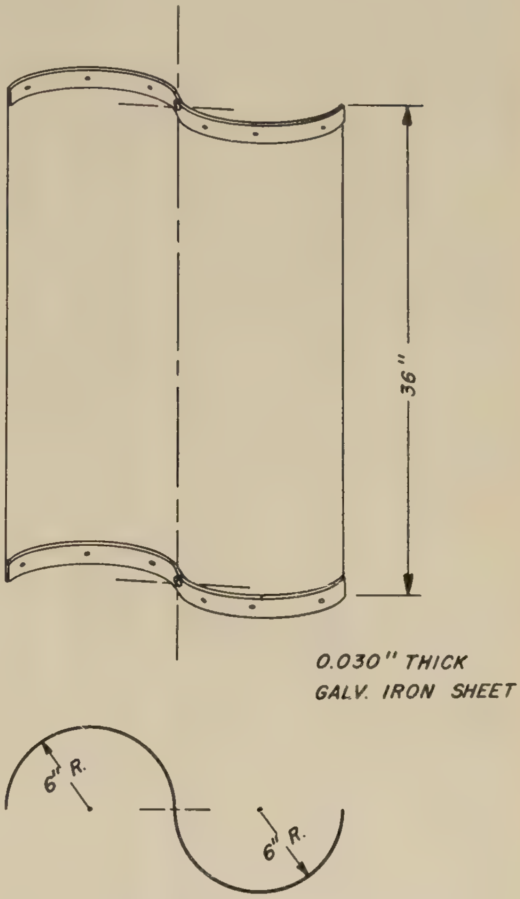

Fig. 3. Detailed sketch of the construction of the rotor.

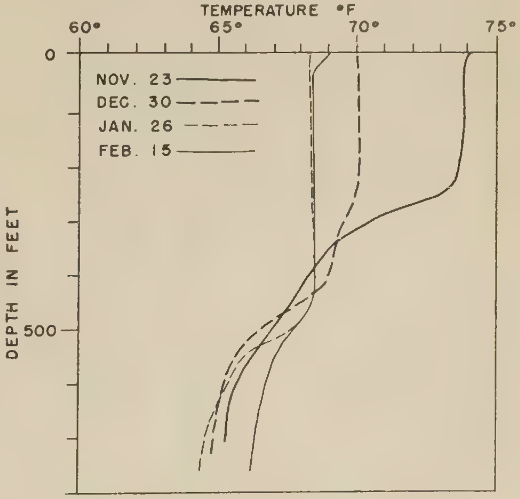

Fig. 4. Sample bathythermograph soundings showing the mixed water conditions prevailing through most of the period of measurements.

channel; and the sense of rotation of the rotor was reversed in some of the later buoys in order to eliminate this possible source of error from the data.

The telemetering itself is done in the following manner: the various sensing elements operate variable electric resistances, which produce variable audio frequencies which in turn are transmitted as a modulation of the radio frequencies. It is believed that adequate precautions were taken to prevent possible errors in the telemetering system. Messrs. Robert G. Walden and Donald Parson, Jr. collaborated with me in the design and construction of the buoys.

II. Discussion of data

The original data from the buoys, including all cases where the buoys were not near to the shore of the island, is collected in Table I. Perhaps the most striking feature of this data

Table 1. Data for all cases where buoys were beyond island influence

	Local	Wind		Buoy	Trans.	Current		Wind
	Time	dir.	mph	No.	Time	dir.	knots	Vane
1953 Oct. 27 TM 0003	0000	200	1	3	0024	020	0.27	330
	0300	200	1	3	0325	035	0.85	240
	0600	200	1	3	0625	060	0.74	225
	0900	160	6	3	0922	105	0.10	160
	1200	180	8	3	1222	305	0.69	000
	1500	180	5	3	1522	020	0.61	000
	1800	190	3	3	1823	100	0.72	240
	2100	200	5	3	2123	195	0.69	130
Oct. 28 TM 0058	0000	200	7	3	0023	250	0.46	070
	0300	180	8	3	0323	310	0.61	030
	0600	170	8	3	0623	340	0.74	000
	0900	170	10	3	0923	340	0.54	320
	1200	180	15	3	1223	320	-	000
				4	1243	035	0.74	000
	1500	180	16	3	1522	000	0.50	350
	1800	180	15	4	1844	345	0.64	165
	2100	170	19	3	2122	000	0.51	310
				4	2145	080	0.34	340
Oct. 29 TM 0148	0000	180	23	3	0022	010	0.86	290
	0300	200	25	3	0321	035	0.48	290
				4	0346	080	0.75	350
	0600	190	23	3	0621	100	0.98	250
				4	0646	080	0.30	350
	0900	200	23	3	0922	100	0.98	270
				4	0949	000	0.28	030
	1200	200	25	3	1222	050	0.69	290
				4	1249	055	0.70	330
	1500	200	26	3	1522	055	0.77	240
				4	1549	070	0.90	000
	1800	200	25	3	1822	030	2.00	285
				4	1849	090	0.93	340
	2100	200	23	3	2122	050	2.64	300
				4	2149	045	0.05	000
1953 Oct. 30 TM 0234	0000	200	27	3	0022	105	0.54	260
				4	0050	055	0.58	000
	0300	200	26	3	0322	040	0.83	310
				4	0350	080	0.67	300
	0600	200	27	3	0622	070	0.90	300
				4	0650	060	1.01	355
	0900	200	26	3	0921	060	0.62	260
				4	0931	340	0.51	020
	1200	200	26	3	1221	035	0.83	330
				4	1252	010	0.21	020
	1500	200	26	3	1521	080	0.82	010
				4	1552	090	0.74	355
	1800	190	22	3	1821	200	1.01	340
				4	1854	070	0.88	340
	2100	270	5	3	2120	235	0.46	030
				4	2152	090	0.86	000
Oct. 31 TM 0317	0000	260	2	3	0020	290	0.80	270
				4	0100	090	0.08	000
	0300	000	14	3	0320	150	0.80	000
				4	0400	105	0.64	010
	0600	000	13	3	0620	125	0.80	000
				4	0700	145	0.69	350
	0900	100	11	3	0920	220	0.37	000
				4	1005	-	1.12	335
	1200	320	9	3	1220	170	0.70	290
				4	1308	-	0.32	145
	1500	270	3	3	1520	010	0.75	000
				4	1610	-	0.26	010
	1800	220	7	3	1820	035	0.98	315
				4	1912	-	0.74	110
	2100	220	9	3	2120	105	0.34	000
				4	2212	-	0.70	000
Nov. 1 TM 0357	0000	320	9	3	0020	105	0.77	000
				4	0114	-	0.92	215
	0300	320	7	3	0320	000	0.77	055
				4	0418	-	0.24	040
	0600	280	7	3	0620	070	0.67	020
				4	0718	-	0.30	245
	0900	270	11	3	0920	105	-	000
				4	1018	-	0.77	290
	1200	330	12	3	1220	070	0.48	350
				4	1317	-	0.90	000
	1500	320	12	3	1520	125	0.74	315
				4	1618	-	0.77	000
	1800	340	12	3	1819	150	0.75	270
				4	1918	-	0.03	000
	2100	350	7	3	2119	210	0.88	290
				4	2220	-	0.67	040
1953 Nov. 2 TM 0437	0000	340	3	3	0019	190	0.42	300
				4	0120	-	2.08	035
	0300	340	5	3	0319	180	0.67	290
				4	0420	-	2.48	060
	0600	000	6	3	0619	250	0.77	045
				4	0720	-	0.30	270
	0900	070	2	3	0920	230	0.88	280
				4	1023	-	0.27	000
	1200	040	6	3	1220	215	0.26	000
				4	1322	-	0.64	180
	1500	000	7	3	1520	180	0.61	000
				4	1623	-	1.76	090
	1800	040	6	3	1820	205	0.64	000
				4	1923	-	-	000
	2100	-	-	3	2119	260	0.67	310
				4	2224	-	0.19	210
Nov. 3 TM 0517	0000	045	8	3	0019	245	0.74	290
				4	0124	-	0.37	320
	0300	110	3	3	0319	210	0.51	300
				4	0424	-	0.74	280
	0600	060	5	3	0619	215	0.61	315
				4	0724	-	0.77	120
	0900	045	11	3	0920	210	0.67	000
				4	1024	-	0.88	350
	1200	045	10	3	1222	215	0.67	320
				4	1325	-	0.13	000
	1500	045	8	3	1522	215	0.30	340
				4	1626	-	0.32	340
	1800	-	-	3	1820	190	-	010
				4	1926	-	0.74	-
	2100	030	5	3	2123	220	0.54	310
				4	2226	-	0.62	210
Nov. 4 TM 0558	0000	045	3	3	0020	260	0.62	250
				4	0126	-	0.88	110
	0300	050	2	3	0320	320	0.54	260
				4	0420	-	0.29	135
	0600	045	3	3	0626	330	0.53	180
				4	0726	-	0.03	325
	0900	023	5	3	0926	350	0.56	130
				4	1027	-	0.57	335
	1200	010	5	3	1228	105	0.56	060
				4	1327	-	0.54	325
	1500	000	3	3	1500	330	0.54	210
				4	1600	-	0.69	270
	1800	005	3	3	1831	330	0.61	210
				4	1927	-	0.77	225
	2100	005	4	3	2133	330	0.43	110
1953 Nov. 5 TM 0640	0000	-	calm	3	0035	025	0.42	090
				4	0136	-	0.11	020
	0300	010	5	3	0300	050	0.58	060
				4	0436	-	0.56	305
	0600	015	3	3	0600	280	0.62	160
	0900	032	2	3	0941	270	0.69	215
	1200	055	3	3	1243	310	0.46	150
				4	1350	-	0.69	280
	1500	075	4	3	1545	310	0.69	085
				4	1654	-	0.10	000
	1800	075	5	3	1845	330	0.62	135
				4	1959	-	0.37	315
	2100	105	8	3	2146	010	0.61	280
				4	2303	-	0.54	000
Nov. 6 TM 0725	0000	110	7	3	0047	000	0.72	000
				4	0205	-	0.64	000
	0300	122	11	3	0347	300	0.19	310
				4	0505	-	0.90	000
	0600	120	5	3	0647	340	0.77	330
				4	0805	-	0.34	000
	0900	120	12	3	0946	010	0.72	340
				4	1109	-	0.14	340
	1200	120	14	3	1246	020	0.75	260
				4	1409	-	0.70	340
	1500	135	15	3	1547	340	0.48	280
				4	1710	-	0.67	325
	1800	135	13	3	1846	320	0.77	350
				4	2013	-	0.94	100
	2100	135	12	3	2146	340	0.72	300
				4	2317	-	0.18	355

(Cont.)

	Local	Wind		Buoy	Trans.	Current		Wind
	Time	dir.	mph	No.	Time	dir.	knots	Vane
Nov. 7 TM 0813	0000	140	-	3	0046	000	0.78	330
				4	0217	-	0.25	315
	0300	150	11	3	0346	020	0.51	290
				4	0519	-	0.69	350
	0600	180	-	3	0646	030	0.77	290
				4	0822	-	0.85	075
	0900	180	-	3	0946	010	0.83	315
				4	1123	-	0.80	005
	1200	220	-	3	1246	350	0.59	310
				4	1424	-	0.03	015
	1500	195	-	3	1545	035	0.43	340
				4	1727	-	0.51	010
	1800	123	7	3	1845	050	0.74	350
	2100	220	6	3	2145	290	-	000
				4	2333	-	0.83	025
1953 Nov. 8 TM 0905	0000	220	calm	3	0045	160	0.66	000
	0300	225	calm	3	0345	170	0.70	000
	0600	265	2	3	0645	215	0.48	340
	0900	050	4	3	0944	210	0.74	310
	1200	070	5	3	1244	230	0.82	280
	1500	050	6	-	-	-	-	-
	1800	050	5	3	1844	250	0.69	270
	2100	060	6	3	2144	240	0.75	270
Nov. 9 TM 0958	0000	015	6	3	0043	240	0.72	000
	0300	060	6	3	0343	225	0.64	290
	0600	080	3	3	0642	250	0.54	290
	0900	078	7	3	0942	230	0.67	320
	1200	120	7	-	-	-	-	-
	1500	070	3	3	1542	280	0.74	260
	1800	085	6	3	1841	305	0.43	240
	2100	080	6	3	2141	220	0.58	000
Nov. 10 TM 1053	0000	098	5	3	0041	220	0.59	010
	0300	098	3	-	-	-	-	-
	0600	090	3	3	0640	125	0.64	110
	0900	095	2	3	0940	000	0.27	270
	1200	090	3	3	1240	050	0.58	235
	1500	090	1	3	1539	060	0.64	240
	1800	-	calm	3	1839	035	0.58	270
	2100	-	calm	3	2138	000	0.69	340
Nov. 11 TM 1147	0000	-	calm	3	0037	030	0.18	350
	0300	240	3	3	0337	040	0.72	300
	0600	240	3	3	0637	105	0.64	260
	0900	220	7	-	-	-	-	-
	1200	190	10	3	1238	035	0.62	290
Nov. 25	0000	140	6	2	0048	010	0.72	280
	0300	140	7	2	0348	015	0.85	300
	0600	140	7	2	0648	010	0.37	310
	0900	150	8	2	0945	020	0.77	305
	1200	175	11	2	1236	055	0.67	295
	1500	175	11	2	1534	110	0.80	070
	1800	180	10	2	1830	090	0.37	290
	2100	180	8	2	2128	095	0.80	225
Nov. 26 TM 0027	0000	185	15	2	0025	315	0.70	030
	0300	185	11	-	-	-	-	-
	0600	190	14	2	0625	005	0.62	020
	0900	190	11	-	-	-	-	-
	1200	185	15	2	1216	060	0.59	350
	1500	185	18	2	1514	020	0.69	350
	1800	200	14	2	1812	035	0.80	330
	2100	195	23	2	2109	045	0.37	340
1953 Nov. 27 TM 0112	0000	210	12	2	0007	010	0.72	010
	0300	260	11	2	0305	080	0.70	350
	0600	295	14	2	0602	090	0.83	350
	0900	295	14	2	0900	145	0.37	305
	1200	295	10	2	1158	145	0.82	300
	1500	295	8	2	1456	190	0.70	235
	1800	285	3	2	1753	215	0.80	225
	2100	-	calm	2	2050	255	0.37	210
Nov. 28 TM 0154	0000	-	calm	-	-	-	-	-
	0300	280	-	2	0245	305	0.67	010
	0600	280	-	2	0540	055	0.77	320
	0900	280	-	2	0842	070	0.54	305
	1200	190	6	2	1140	070	0.48	305
	1500	270	5	2	1437	090	0.77	290
	1800	225	3	2	1735	090	0.78	320
	2100	255	2	2	2033	090	0.74	330
Nov. 29 TM 0234	0000	255	3	-	-	-	-	-
	0300	255	6	2	0230	095	0.67	340
	0600	260	8	2	0528	125	0.59	325
	0900	340	12	2	0824	110	0.75	335
	1200	350	10	2	1122	110	0.48	000
	1500	000	9	2	1420	135	0.69	000
	1800	015	7	2	1717	180	0.69	335
	2100	050	6	2	2016	165	0.69	020
Nov. 30 TM 0314	0000	040	5	-	-	-	-	-
	0300	050	5	-	-	-	-	-
	0600	040	3	2	0510	090	0.88	105
	0900	065	5	-	-	-	-	-
	1200	095	6	2	1105	075	0.37	165
	1500	080	7	2	1404	010	0.26	240
	1800	070	4	2	1701	030	0.72	260
	2100	-	calm	-	-	-	-	-
Dec. 1 TM 0354	0000	100	10	-	-	-	-	-
	0300	120	10	-	-	-	-	-
	0600	125	11	-	-	-	-	-
	0900	110	15	2	1050	010	-	350
	1200	150	6	2	1348	035	0.70	350
	1500	230	24	2	1646	090	0.37	295
	1800	225	22	2	1944	080	0.86	275
	2100	270	15	2	2242	100	0.85	310
1953 Dec. 2 TM 0436	0000	270	12	2	0140	105	0.80	330
	0300	275	14	2	0439	100	0.61	295
	0600	280	22	2	0737	070	0.91	350
	0900	285	20	2	1035	115	0.93	020
	1200	285	20	2	1333	055	0.48	350
	1500	290	18	2	1631	100	0.91	350
	1800	320	19	2	1929	115	0.80	350
	2100	330	18	2	2228	120	0.90	325
Dec. 3 TM 0520	0000	330	15	2	0126	095	0.45	005
	0300	330	14	2	0424	145	0.85	335
	0600	330	15	2	0722	180	0.86	340
	0900	330	16	2	1022	215	0.59	345
	1200	335	15	2	1322	175	0.72	350
	1500	340	16	2	1620	140	0.82	350
	1800	000	12	2	1919	205	0.91	340
	2100	000	11	2	2118	260	0.40	335
Dec. 4 TM 0607	0000	015	7	2	0110	130	0.83	350
	0300	015	8	2	0410	350	0.75	210
	0600	025	6	-	-	-	-	-
	0900	030	7	-	-	-	-	-
	1200	055	7	-	-	-	-	-
	1500	075	8	-	-	-	-	-
	1800	070	6	-	-	-	-	-
	2100	095	9	-	-	-	-	-
Dec. 5 TM 0658	0000	095	6	-	-	-	-	-
	0300	095	5	-	-	-	-	-
	0600	100	4	-	-	-	-	-
	0900	120	4	-	-	-	-	-
	1200	020	2	8	1228	055	-	210
	1500	080	4	8	1528	025	0.06	220
	1800	080	4	8	1828	320	0.49	305
	2100	080	2	8	2128	195	0.34	040
Dec. 6 TM 0752	0000	075	3	8	0028	185	0.39	015
	0300	085	2	8	0328	230	0.43	325
	0600	080	4	8	0628	330	0.69	280
	0900	080	5	8	0929	010	0.36	250
	1200	060	4	8	1359	030	0.56	240
	1500	075	6	8	1659	080	0.60	230
	1800	080	5	8	1959	290	0.42	010
	2100	100	6	8	2127	305	0.34	000

(Cont.)

	Local Time	Wind		Buoy No.	Trans. Time	Current		Wind Vane
		dir.	mph			dir.	knots	
1953 Dec. 7 TM 0847	0000	150	5	8	0027	000	0.00	315
	0300	180	10	8	0327	005	0.49	000
	0600	180	6	8	0627	350	0.59	350
	0900	220	8	8	0926	015	0.49	335
	1200	225	12	8	1224	080	0.43	315
	1500	230	12	8	1526	130	0.43	230
	1800	245	3	8	1825	210	0.00	210
	2100	260	2	8	2125	230	0.42	190
Dec. 8 TM 0943	0000	260	2	8	0025	230	0.56	185
	0300	260	2	8	0325	215	0.46	225
	0600	-	calm	8	0625	240	0.56	140
	0900	010	4	8	0925	215	0.13	295
	1200	035	5	8	1225	200	0.36	020
	1500	080	6	8	1525	260	0.56	350
	1800	125	3	8	1825	280	0.42	015
	2100	125	4	8	2125	285	0.46	245
Dec. 9 TM 1037	0000	125	4	8	0025	350	0.60	300
	0300	130	6	8	0325	330	0.07	320
	0600	130	7	8	0625	335	0.52	315
	0900	120	6	8	0925	305	0.49	330
	1200	100	8	8	1225	035	0.46	315
	1500	135	11	8	1525	030	0.52	300
	1800	120	11	8	1825	080	0.56	215
	2100	130	7	8	2125	200	0.13	080
Dec. 10 TM 1129	0000	120	7	8	0157	090	0.63	225
	0300	150	11	8	0325	080	0.49	245
	0600	180	14	8	0625	080	0.63	275
	0900	180	15	8	0923	080	0.39	280
	1200	200	18	8	1223	080	0.29	305
	1500	225	17	8	1521	080	0.83	285
	1800	225	15	8	1821	085	0.95	295
	2100	255	14	8	2121	095	0.53	260
Dec. 11 TM 1219	0000	-	calm	8	0021	130	0.70	260
	0300	240	4	8	0321	110	0.90	260
	0600	240	4	8	0621	150	0.63	300
	0900	230	6	8	0921	150	0.13	290
	1200	060	3	8	1221	195	0.83	115
	1500	080	10	8	1521	195	0.85	000
	1800	065	10	8	1821	200	0.70	010
	2100	090	11	8	2121	195	0.00	020
1953 Dec. 12 TM 1308	0000	090	12	8	0021	230	0.49	010
	0300	100	10	8	0321	190	0.62	030
	0600	110	10	8	0621	195	0.49	030
	0900	120	11	8	0921	190	0.34	100
	1200	150	11	8	1221	215	0.42	055
	1500	180	12	8	1521	205	0.17	080
	1800	200	14	8	1821	120	0.32	190
	2100	220	12	8	2121	100	0.40	225
Dec. 13 TM 1356	0000	220	15	8	0021	090	0.46	215
	0300	225	15	8	0321	180	0.46	185
	0600	225	14	8	0621	170	0.56	200
	0900	230	13	8	0921	120	0.07	235
	1200	240	17	8	1221	125	0.40	240
	1500	240	14	8	1521	120	0.60	235
	1800	220	11	8	1821	180	0.84	180
	2100	210	11	8	2121	185	0.07	135
Dec. 14 TM 1445	0000	220	13	8	0021	195	0.76	145
	0300	220	12	8	0321	120	0.73	215
	0600	210	13	8	0621	170	0.77	160
	0900	220	13	8	0918	160	0.39	160
	1200	220	15	8	1218	160	0.98	135
	1500	210	14	8	1521	195	0.70	140
	1800	210	14	8	1818	160	0.29	160
	2100	210	18	8	2117	185	0.87	130
Dec. 15 TM 1536	0000	210	15	8	0017	250	0.60	095
	0300	210	17	8	0317	280	0.49	035
	0600	210	16	8	0617	155	0.07	170
	0900	220	20	8	0917	150	-	220
	1200	210	23	-	-	-	-	-
	1500	270	10	-	-	-	-	-
	1800	330	12	-	-	-	-	-
	2100	350	16	-	-	-	-	-
Dec. 16 TM 1630	0000	350	12	-	-	-	-	-
	0300	345	9	-	-	-	-	-
	0600	015	7	-	-	-	-	-
	0900	045	3	-	-	-	-	-
	1200	030	3	-	-	-	-	-
	1500	350	4	7	1538	340	-	-
	1800	000	6	7	1838	310	0.53	-
	2100	000	5	7	2138	240	0.62	-
1953 Dec. 17 TM 1727	0000	330	3	7	0038	075	0.43	-
	0300	300	5	7	0338	175	0.07	-
	0600	280	10	7	0638	125	0.62	-
	0900	300	12	7	0938	170	0.52	-
	1200	320	14	7	1238	185	0.60	-
	1500	330	15	7	1537	270	0.55	-
	1800	330	19	7	1837	295	0.17	-
	2100	320	17	7	2137	150	0.60	-
Dec. 18 TM 1827	0000	320	14	7	0037	250	0.60	-
	0300	320	17	7	0337	215	0.45	-
	0600	320	14	7	0637	265	0.77	-
	0900	310	14	7	0937	220	0.00	-
	1200	310	9	7	1237	185	0.78	-
	1500	320	10	7	1537	190	0.81	-
	1800	320	18	7	1837	225	0.69	-
	2100	320	21	7	2137	235	0.00	-
Dec. 19 TM 1928	0000	320	23	7	0037	210	0.64	-
	0300	325	12	7	0337	255	0.70	-
	0600	325	18	7	0637	220	0.78	-
	0900	325	17	7	0937	225	0.31	-
	1200	320	18	7	1237	195	0.76	-
	1500	320	18	7	1537	235	0.70	-
	1800	320	18	7	1837	220	0.80	-
	2100	350	15	7	2137	190	0.18	-
Dec. 20 TM 2028	0000	350	11	7	0037	225	0.70	-
	0300	345	9	7	0337	190	0.70	-
	0600	340	6	7	0637	180	0.60	-
	0900	340	6	7	0936	250	0.45	-
	1200	340	6	7	1236	225	0.31	-
	1500	270	2	7	1536	210	0.62	-
	1800	270	2	7	1836	210	0.53	-
	2100	270	3	7	2136	240	0.55	-
Dec. 21 TM 2124	0000	270	7	7	0036	120	0.42	-
	0300	270	6	7	0336	145	0.07	-
	0600	-	calm	7	0636	115	0.62	-
	0900	270	2	7	0936	095	0.59	-
	1200	200	15	7	1236	095	0.46	-
	1500	195	18	7	1536	065	0.50	-
	1800	210	15	7	1836	065	0.28	-
	2100	210	16	7	2136	065	0.38	-
1953 Dec. 22 TM 2216	0000	210	22	7	0036	065	0.64	-
	0300	210	22	7	0336	065	0.70	-
	0600	210	22	7	0636	065	0.67	-
	0900	210	19	7	0935	095	0.15	-
	1200	210	22	7	1235	085	0.69	-
	1500	210	19	7	1535	075	0.64	-
	1800	210	16	7	1835	095	0.69	-
	2100	210	15	7	2135	110	0.25	-
Dec. 23 TM 2303	0000	230	9	7	0035	090	0.36	-
	0300	215	6	7	0335	110	0.73	-
	0600	-	-	7	0635	125	0.60	-
	0900	250	4	7	0935	135	0.52	-
	1200	260	6	7	1235	165	0.21	-
	1500	260	6	7	1534	105	0.13	-
	1800	250	6	-	-	-	-	-
	2100	250	9	7	2134	105	0.52	-
Dec. 24 TM 2348	0000	260	17	7	0034	230	0.52	-
	0300	260	20	7	0334	110	0.60	-
	0600	260	21	7	0634	120	0.13	-
	0900	260	23	7	0934	095	0.70	-
	1200	270	12	7	1234	130	0.70	-
	1500	030	8	7	1534	195	0.70	-
	1800	020	11	7	1834	345	0.34	-
	2100	000	10	7	2134	275	0.18	-

(Cont.)

	Local Time	Wind		Buoy No.	Trans. Time	Current		Wind Vane
		dir.	mph			dir.	knots	
Dec. 25	0000	000	13	7	0034	250	0.73	-
	0300	020	10	7	0334	285	0.70	-
	0600	030	9	7	0634	270	0.66	-
	0900	045	5	7	0934	300	0.17	-
	1200	045	3	7	1234	315	0.43	-
	1500	120	3	7	1534	065	0.57	-
	1800	180	7	7	1834	065	0.53	-
	2100	210	12	7	2134	065	0.49	-
Dec. 26 TM 0029	0000	210	22	7	0034	065	0.41	-
	0300	210	20	7	0334	130	0.20	-
	0600	210	32	7	0634	075	0.74	-
	0900	250	18	7	0932	105	0.71	-
	1200	320	12	7	1232	175	0.73	-
	1500	320	11	7	1532	190	0.07	-
1953 Dec. 30 TM 0313	0000	250	14	-	-	-	-	-
	0300	270	9	-	-	-	-	-
	0600	270	8	-	-	-	-	-
	0900	260	7	-	-	-	-	-
	1200	270	9	6	1346	115	0.66	280
	1500	270	7	6	1527	130	0.46	280
				6	1646	150	0.07	225
	1800	250	6	6	1827	145	0.85	225
				6	1946	275	0.71	180
	2100	250	6	6	2127	255	0.59	175
				6	2246	255	0.71	175
Dec. 31 TM 0359	0000	250	12	6	0027	130	0.67	230
				6	0146	090	0.57	230
	0300	250	8	6	0327	355	0.50	080
				6	0446	090	0.20	355
	0600	250	12	6	0627	090	0.27	355
				6	0746	065	0.77	000
	0900	250	18	6	0948	095	0.66	240
				6	1048	105	0.66	240
	1200	250	22	6	1228	115	0.70	240
				6	1348	105	0.90	255
	1500	250	22	6	1529	085	0.77	240
				6	1649	095	0.17	225
	1800	250	21	6	1828	105	0.69	145
				6	1949	095	0.78	025
	2100	330	27	6	2128	115	0.74	005
				6	2249	130	0.87	355
1954 Jan. 1 TM 0448	0000	330	25	6	0028	130	0.97	005
				6	0149	150	0.80	015
	0300	330	24	6	0328	120	0.43	015
				6	0449	115	0.69	355
	0600	330	21	6	0628	120	0.87	035
				6	0749	160	0.71	335
	0900	330	18	6	0928	140	0.80	030
				6	1049	125	0.74	015
	1200	330	16	6	1228	130	0.71	025
				6	1351	120	0.08	025
	1500	310	13	6	1651	120	0.71	120
	1800	310	11	6	1830	115	0.59	030
				6	1951	105	0.55	355
	2100	310	10	6	2130	055	0.74	060
				6	2251	110	0.74	000
1954 Jan. 2 TM 0540	0000	326	13	6	0030	105	0.63	295
				6	0151	120	0.11	355
	0300	330	13	6	0330	095	0.48	045
				6	0451	120	0.00	355
	0600	330	13	6	0630	120	0.59	025
				6	0751	120	0.63	355
	0900	340	11	6	0932	125	0.67	295
				6	1053	130	0.71	355
	1200	340	9	6	1232	160	0.70	030
				6	1353	140	0.21	295
	1500	030	7	6	1532	165	0.24	040
				6	1653	175	1.06	025
	1800	050	3	6	1832	205	0.70	000
				6	1953	185	0.63	040
	2100	-	calm	6	2132	195	0.70	045
				6	2253	145	0.77	125
Jan. 3 TM 0636	0000	-	calm	6	0032	205	0.63	125
				6	0153	165	0.15	170
	0300	-	calm	6	0332	285	0.35	115
				6	0453	220	0.60	100
	0600	060	1	6	0632	210	0.81	140
	0900	120	3	6	0934	270	0.71	055
				6	1054	310	0.85	020
	1200	180	12	6	1234	285	0.67	025
				6	1356	295	0.11	035
	1500	300	4	6	1534	285	0.67	060
				6	1656	305	0.66	025
	1800	210	20	6	1834	045	0.59	355
				6	1956	340	0.63	355
	2100	200	19	6	2134	320	0.70	015
				6	2256	025	0.85	185
Jan. 4 TM 0732	0000	210	19	6	0034	025	0.59	355
				6	0156	030	0.14	355
	0300	210	22	6	0334	350	0.35	355
				6	0456	005	0.77	010
	0600	210	19	6	0634	340	0.67	025
				6	0756	055	0.77	060
	0900	210	20	6	0936	031	-	001
				6	1056	015	0.63	358
	1200	210	23	6	1236	022	0.77	356
				6	1356	030	0.08	-
	1500	210	19	6	1556	005	1.68	002
	1800	240	7	6	1836	-	0.13	-
				6	1956	102	1.67	356
	2100	000	9	6	2136	110	0.08	-
				6	2256	212	-	097
1954 Jan. 5 TM 0828	0000	020	8	6	0036	301	0.35	-
				6	0156	212	0.20	-
	0300	035	4	6	0336	147	1.40	059
				6	0456	175	0.35	000
	0600	060	5	6	0636	298	0.85	041
				6	0756	297	0.77	042
	0900	038	4	6	0940	295	0.67	105
				6	1056	270	0.53	356
	1200	085	5	6	1240	212	0.63	048
				6	1356	212	0.00	059
	1500	063	5	6	1540	339	0.66	012
				6	1700	264	0.69	012
	1800	090	10	6	1842	264	0.13	042
	2100	120	14	6	2142	270	0.41	026
Jan. 6 TM 0923	0000	170	17	6	0042	270	0.11	031
				6	0200	297	0.27	-
	0300	180	19	6	0342	311	-	000
				6	0500	330	0.62	356
	0600	185	19	6	0642	321	0.62	358
				6	0800	330	0.59	018
	0900	220	14	6	0942	005	0.74	352
				6	1100	201	0.83	000
	1200	225	9	6	1242	032	0.56	000
				6	1400	076	0.27	020
	1500	260	6	6	1542	076	0.66	338
				6	1700	060	0.62	-
	1800	260	8	6	1842	100	0.87	338
				6	2000	041	0.60	-
	2100	225	14	-	-	-	-	-
Jan. 7 TM 1015	0000	220	24	-	-	-	-	-
	0300	215	26	-	-	-	-	-
	0600	210	20	-	-	-	-	-
	0900	200	16	6	0942	153	-	000
				6	1100	121	0.63	338
	1200	305	15	6	1242	119	0.21	000
				6	1400	152	-	338
	1500	305	15	6	1542	130	-	338
	1800	315	16	-	-	-	-	-
	2100	315	20	6	2142	092	-	000
				6	2300	066	0.27	-
1954 Jan. 8 TM 1105	0000	315	20	6	0042	085	0.88	338
				6	0200	100	0.11	000
	0300	320	19	6	0342	110	0.43	000
				6	0500	169	0.88	301
	0600	330	20	6	0800	154	0.56	283
	0900	330	22	6	0944	160	-	275
				6	1100	122	0.10	000
	1200	330	20	6	1244	131	0.74	000
	1500	330	20	6	1545	103	0.77	000
				6	1700	155	0.90	000
	1800	335	22	6	1845	158	0.07	338
				6	2000	160	0.27	000
	2100	335	20	-	-	-	-	-

(Cont.)

	Local	Wind		Buoy	Trans.	Current		Wind
	Time	dir.	mph	No.	Time	dir.	knots	Vane
Jan. 9	0000	330	19	-	-	-	-	-
TM 1154	0300	330	13	6	0500	270	-	000
	0600	345	15	6	0642	192	0.43	000
	0900	000	10	6	1100	168	0.56	357
	1200	000	13	6	1242	211	0.83	338
				6	1400	202	0.85	000
	1500	000	7	6	1548	230	0.56	000
				6	1700	168	0.27	-
	1800	010	5	6	1848	239	0.64	224
	2100	-	calm	6	2128	097	0.56	085
Jan. 10	0000	-	calm	-	-	-	-	-
TM 1243	0300	-	calm	-	-	-	-	-
	0600	225	6	-	-	-	-	-
	0900	225	7	-	-	-	-	-
	1200	220	10	6	1249	330	-	356
				6	1400	329	0.55	356
	1500	190	12	6	1548	350	0.69	000
				6	1700	358	0.55	000
	1800	190	14	-	-	-	-	-
	2100	185	17	-	-	-	-	-
Jan. 11	0000	185	14	-	-	-	-	-
TM 1333	0300	195	20	-	-	-	-	-
	0600	220	21	-	-	-	-	-
	0900	225	17	6	0951	349	-	356
				6	1100	005	1.62	000
	1200	220	20	6	1413	357	0.15	000
	1500	210	21	6	1552	008	0.80	301
				6	1700	008	0.83	000
	1800	200	16	-	-	-	-	-
	2100	200	16	-	-	-	-	-
1954 Jan. 12	0000	190	21	-	-	-	-	-
TM 1425	0300	190	21	6	0342	026	-	000
				6	0500	006	0.77	000
	0600	240	26	6	0642	027	0.76	139
				6	0800	008	0.88	003
	0900	245	26	6	0953	041	0.11	352
				6	1141	103	0.83	008
	1200	270	8	6	1253	028	0.46	358
				6	1414	060	0.66	301
	1500	250	10	6	1553	078	0.88	150
	1800	245	8	6	2015	103	-	-
	2100	270	8	6	2153	121	0.21	353
				6	2315	-	1.16	007
Jan. 13	0000	300	11	6	0053	060	0.49	042
TM 1519	0300	300	12	6	0353	152	0.49	264
				6	0515	152	1.10	264
	0600	310	14	6	0653	121	0.84	000
				6	0815	010	0.15	000
	0900	335	21	6	0953	264	0.70	098
				6	1015	264	0.76	221
Jan. 26	0000	355	13	-	-	-	-	-
TM 0107	0300	030	11	-	-	-	-	-
	0600	030	7	-	-	-	-	-
	0900	040	6	-	-	-	-	-
	1200	065	7	9	1245	293	0.35	026
	1500	070	6	9	1545	-	0.56	332
	1800	095	4	9	1845	011	0.66	350
	2100	090	4	9	2145	031	0.71	305
Jan. 27	0000	090	5	9	0047	328	0.20	312
TM 0151	0300	090	4	9	0347	063	0.52	286
	0600	100	4	9	0647	048	0.57	287
	0900	105	5	9	0946	045	0.66	311
	1200	100	6	9	1246	005	0.49	260
	1500	090	3	9	1545	334	0.34	328
	1800	-	calm	9	1845	350	0.59	338
	2100	-	calm	9	2145	034	1.54	348
1954 Feb. 8	0000	280	10	-	-	-	-	-
TM 1221	0300	-	-	-	-	-	-	-
	0600	-	-	-	-	-	-	-
	0900	-	-	-	-	-	-	-
	1200	150	7	-	-	-	-	-
	1500	140	14	14	1637	307	-	000
	1800	180	17	14	1937	001	0.72	000
				14	2043	359	0.45	312
	2100	225	24	-	-	-	-	-
Feb. 9	0000	265	26	-	-	-	-	-
TM 1315	0300	270	50	-	-	-	-	-
	0600	260	43	-	-	-	-	-
	0900	265	30	14	1040	100	-	000
				14	1145	095	0.96	270
	1200	270	18	14	1340	096	1.08	280
	1500	280	18	14	1445	140	1.08	336
	1800	280	20	-	-	-	-	-
	2100	280	23	-	-	-	-	-

Notes on Table I.

Buoys 8, 9, and 14 were all rigged as shown in Figure 2; buoys 6 and 7 were rigged with the deep drag on a bridle directly beneath the can; buoys 2, 3 and 4 were rigged the same as Figure 2, but the deep drag was replaced by another rotor similar to that at the surface. The depth of the deep drag, of the surface rotor, and the Magnus correction applied in determining current direction from the rough data, were as follows:

Buoy No.	Depth of deep drag (or rotor) (feet)	Depth of surface rotor (feet)	Current direction correction
2	150	8	− 10°
3	200	8	− 10°
4	150	8	− 10°
6	170	8	unknown
7	120	8	− 25°
8	530	13	− 10°
9	150	8	+ 10°
14	300	10	+ 10°

It is probable that there is a systematic error in all angles measured by buoy 6.

The notation "TM" means the Bermuda Time (GMT − 4 hours) of Greenwich upper transit of the moon. The anemometers on the buoys were so unreliable (due to circuit troubles) that all of their data are omitted. Winds tabulated are those on a 50 foot mast at the observatory at Bermuda. The exposure was not ideal, there being several hills, and a large building in the neighborhood. Particularly, the anemometer is partly sheltered from west winds.

The notation 'Trans. Time" means the Bermuda time at which the buoy wireless transmission was received. The current direction is the instantaneous magnetic direction of the surface current (vectorial difference of surface and deep) with the above corrections applied. The current speed is an average for the previous three hours (in the case of buoy 6, 90 minutes).

The figures under "Wind Vane" are angle between the geographical orientation of the buoy and the wind direction measured by the vane on the buoy. Thus an angle of 000° means that the instantaneous wind and uncorrected current vector point in the same direction; an angle of 030° means the uncorrected current is 30° to the left of the wind; an angle of 320° means the uncorrected current is 40° to the right of the wind.

is the considerable irregularity of the currents even during days while the wind is fairly steady. In his discussion of the current measurements which he made on board the "Armauer Hansen" in 1930, Ekman (1953) has called this irregular motion a kind of "macro-turbulence". As a result it is difficult to extract from the data definite statements about such things as: (i) the deviation of the surface current from the direction of the surface wind; and (ii) the ratio of current speed to the speed of the wind producing it. Ekman (1953) attempted to analyze his data for "Armauer Hansen" anchor station D in order to find the answer to these questions and to delineate the drift current spiral as a function of depth. Because of the macro-turbulence the results of his analysis were disappointingly indefinite. The purpose of such an analysis, of course, was to verify in the deep ocean the results of his theory (Ekman 1905).

Table 2. Total number of vane readings (cumulative) for each 10° angle of deviation of current from wind

Buoys 2, 3, 4, and 8

170 R	4	010 L	274
160 R	6	020 L	288
150 R	7	030 L	297
140 R	18	040 L	307
130 R	25	050 L	309
120 R	30	060 L	311
110 R	32	070 L	314
100 R	46	080 L	318
090 R	56	090 L	320
080 R	68	100 L	322
070 R	79	110 L	325
060 R	103	120 L	331
050 R	121	130 L	333
040 R	141	140 L	338
030 R	154	150 L	340
020 R	172*	160 L	341
010 R	192	170 L	345
000	223		

*Half the readings are on either side of this point.

The present buoy measurements are confined to the surface. They cover a longer period than those made on the "Armauer Hansen". It is therefore hopeful that certain features of drift currents may emerge more clearly from the confusion of the macro-turbulence.

In order to appreciate how serious an obstacle the macro-turbulence is to a simple analysis of the data, an analysis can be made of all the wind vane readings obtained from buoys 2, 3, 4, and 8 (Table II). The current direction correction due to the Magnus effect on the rotor has been applied. As can be seen, there is a very large scatter of the angle of deviation of the current from the wind; at one time or another every possible angle has occurred. On the average, however, there is a greater frequency of small angles of deviation showing that usually a current does not run against the wind. Moreover, there is a rather definite indication that currents to the right of the wind are more frequent than currents to the left of the wind. The mode of this frequency distribution lies at about 20° to the right of the wind, but it is obvious that this type of analysis of the data, including as it does all cases where the winds were rapidly varying, and all cases with pronounced irregular motions or possible inertial oscillations, gives at best a very diffuse and indefinite kind of answer to question (i). Similar objections can be raised to an attempt to make a gross average determining the ratio of current to wind velocity. A more rational approach is to study individual cases where the wind was observed to be steady. Of course the currents are not exactly steady during the same time. The question arises as to how long a time interval to employ for the study of individual cases. Ekman (1905) indicated that after the onset of a wind the average of the current for the first 24 hours (at 30° N) is a very close approximation to the theoretical current produced by a wind of infinite duration. Thus, in attempting to find answers to questions such as (i) and (ii) (above), 24-hour vectorial averages of wind and current are formed for days of steady wind. The concept of a steady wind is subjective.

The data obtained from October 28—31 is a good sample of the relation between wind and current as it actually appears in nature (Figure 5). During October 28 the wind began to blow toward the north and by midnight was blowing about 23 knots; the currents, which were at first weak and variable, gradually veered to the right of the wind and grew stronger. Early on October 29 the wind itself veered until it blew toward NNE. The current veered, too, and executed a rotatory motion about a mean velocity about 42° to the right of the wind. During the afternoon of October 30, the wind dropped rapidly, and the current began to execute a rotatory (inertial) motion about a zero mean velocity. By October 31,

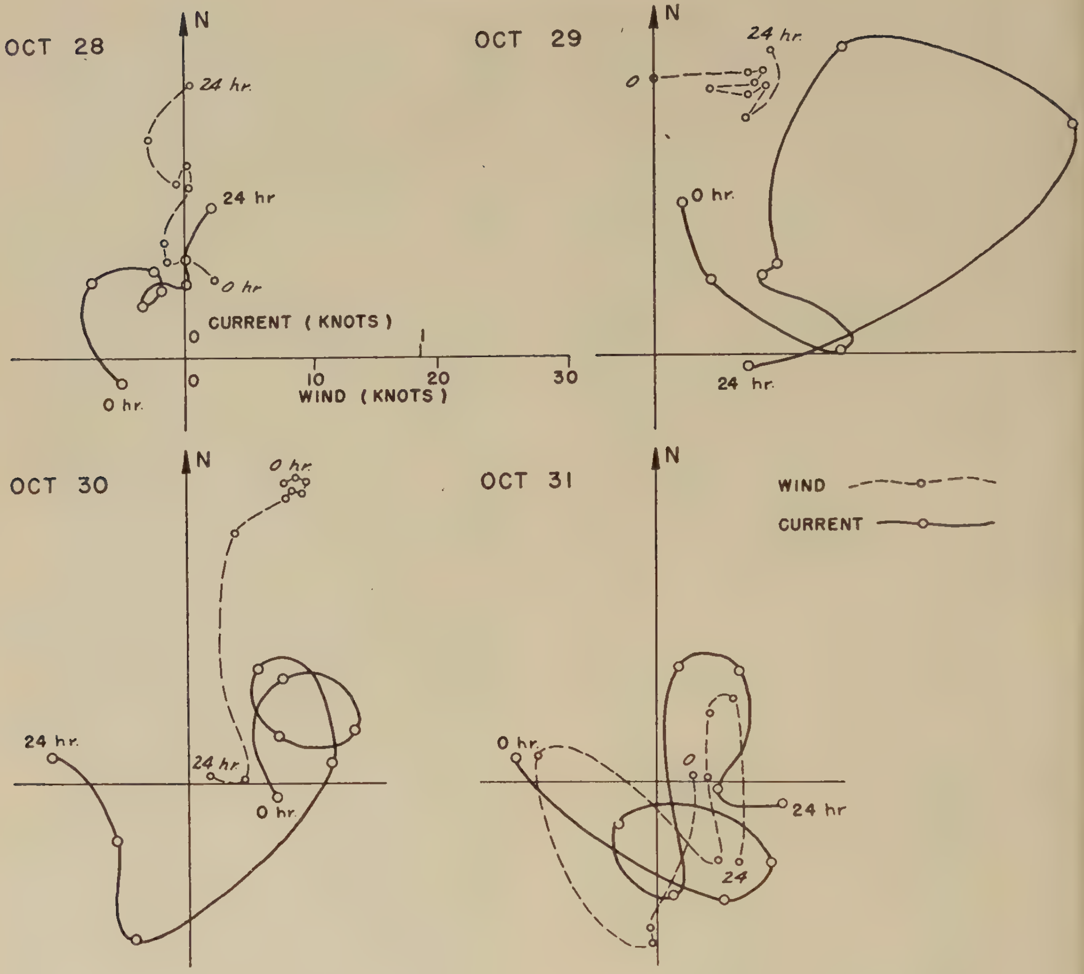

Fig. 5. Sample daily records of wind and current showing the response of the current to a strong wind and the after-effects following it.

the winds were light variable and the motions of the current were very irregular and confused. All evidence of a simple 24-hour inertial period was gone. During the winter of 1953—1954 the currents in the Northwestern Sargasso Sea are most often in a confused state such as depicted on October 31. It is only during days of steady strong winds, and immediately following them, that the theoretical features deduced by Ekman (1905) are clearly defined. Table III contains means of wind and current for all days during which the wind was steady. It was prepared for the purpose of examining the data from the 24-hour mean "case history" point of view.

III. The angle between the wind and current

Two independent ways of measuring the angle between wind and current are possible. The angle may be determined by comparing the mean wind direction at the observatory with direction of the current given by the magnetic compass on the buoy (Method 1). The angle may also be determined directly from the wind vane on the buoy, which

Table 3. 24-hour vectorial means of current and winds for days with steady winds.

Day	Buoy	Wind blows toward	Wind speed (knots)	Current Direction	Current Speed (knots)	Angle of current relative to wind Method (1)	Angle of current relative to wind Method (2)
Oct. 29	3	018	20.0	060	1.09	042 R	070 R
29	4	018	20.0	070	0.70	052 R	000
Nov. 3	3	225	6.1	230	0.51	005 R	025 R
6	3	305	11.2	345	0.64	040 R	045 R
8	3	230	4.4	235	0.72	005 R	040 R
9	3	270	4.5	270	0.57	000	055 R
23(1)	2	285	11.2	315	0.45	030 R	010 R
24	2	335	6.0	335	0.56	000	005 L
26	2	015	13.0	030	0.57	015 R	005 R
Dec. 2-3	2	150	13.0	170	0.50	020 R	020 R
5	8	270	3.0	(2)	0.08	(2)	(2)
6	8	260	4.0	(2)	0.18	(2)	(2)
18	7	140	13.0	220	0.61	080 R	(5)
19	7	145	16.0	225	0.67	080 R	(5)
22	7	030	17.0	075	0.62	045 R	(5)
23	7	060	6.0	115	0.48	055 R	(5)
Jan. 1	6	150	18.0	(3)	0.70	(3)	(3)
3-4	6	030	17.0	(3)	0.50	(3)	(3)
8	6	150	18.0	(3)	0.68	(3)	(3)
11(4)	6	025	18.0	(3)	0.72	(3)	(3)
26-27	9	270	4.0	010	0.48	100 R	055 R
Feb. 9	14	270	23.0	(4)	1.45	(4)	045 R

(1) Current data not available for entire 24 hours, but winds blew steady for previous four days.

(2) Mean direction meaningless because of large oscillatory motions.

(3) Angles have unknown systematic errors due to faulty bridling of Buoy 6.

(4) Current data not available for entire 24 hours.

(5) Wind vane broken.

measures the instantaneous angle between wind and buoy orientation (Method 2). Although this latter method is direct, it is likely to be more erratic due to gustiness of the wind—the sampling of wind direction from wind vane measurements on the buoy is naturally much poorer than the continuous records available at the observatory.

By both methods it is seen that (in agreement with EKMAN, 1905) the current is to the right of the wind, by an angle varying between 30° and 60°. During weak winds there is a greater spread of angles, and on the average the angle appears to be less than for strong winds.

IV. The Ratio of current speed to wind speed

The ratios of current speed to wind speed cited in Table III are about twice what would be expected from Ekman's study. When plotted on a logarithmic scale (Figure 6) these data give some indication that the ratio is not independent of wind speed. There is enough scatter in the data to prevent certainty concerning this point. EKMAN (1905) discussed the case of a "quadratic" law of friction in the sea, and showed that in this case the current speed would be proportional to the three-halves power of the wind speed (rather than linearly proportional). The very limited data at hand suggests the reality of this law of friction, but of course does not prove it. The solid line in Figure 6 depicts the linear law; the dashed line, the three-halves law.

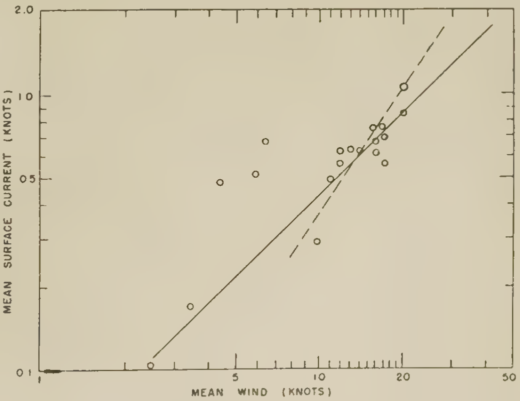

Fig. 6. Logarithmic graph of mean wind against mean surface current for days with steady wind. The solid line has slope of 1.0; the dashed line, slope of 1.5.

Table 4. Inertial amplitudes and phase for days showing 24-hour rotatory currents. All cases are cum sole.

Day	Buoy	Amplitude (knots)	Time of Maximum Northerly Flow	
			Local Mean Solar Time	Greenwich Lunar Time
Oct. 29	3	0.20	1500	1310
30	3	0.25	0800	0530
Nov. 1	3	0.13	0430	0030
5	3	0.10	2030	1400
9	3	0.10	1330	0330
25	2	0.06	0000	0030
27	2	0.25	0000	2230
Dec. 6	8	0.25	0730	2330
7	8	0.20	0630	2145
23	7	0.10	0900	1000
24	7	0.25	1300	1330
26	7	0.06	1100	1200
Jan. 4	6	0.20	0730	0000
6	6	0.20	0900	2330

V. The Presence of inertial oscillations

The design of the rig used on these buoys is not ideal for detecting or studying inertial oscillations because, as Fredholm (Ekman, 1905) showed, the inertial motions penetrate quickly to layers below the depth of frictional influence, and hence the inertial, or quasi-periodic, term in the vectorial difference of velocity is likely to diminish quickly if the deep drag is not much below the depth of frictional influence. Very clear and distinct rotatory currents with 24-hour period were observed on 14 separate days (Table IV); they were quickly damped out (whether by vertical diffusion of momentum, or horizontal dispersion of energy in the form of gravity waves is uncertain). The sense of rotation in every case was *cum sole*. Comparison of phase, to time of transit of the moon results in a complete scatter, thus ruling out the likelihood that these 24-hour periods are lunar tidal currents. There is also no relation to time of day, thus ruling out solar tides.

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The Commonwealth of Massachusetts

DEPARTMENT OF NATURAL RESOURCES
Arthur T. Lyman, Commissioner
DIVISION OF MARINE FISHERIES
Francis W. Sargent, Director

SIXTH REPORT ON

INVESTIGATIONS OF THE SHELLFISHERIES OF MASSACHUSETTS

Prepared by the
WOODS HOLE OCEANOGRAPHIC INSTITUTION
In Accordance with Contract
Effective July 1, 1953

PREFACE

The following report, prepared by Harry J. Turner, Jr., Biologist of the Woods Hole Oceanographic Institution, is a summary of the investigations of methods of improving the shellfish resources of Massachusettts which were carried out in 1953 by the Woods Hole Oceanographic Institution under contract with the Division of Marine Fisheries, Massachusetts Department of Natural Resources.

The investigations were conducted under the leadership of Mr. Turner. Those participating were J. Arthur Posgay, and James Hanks, graduate assistants, and F. T. Carlson, summer assistant. The work was greatly aided by counsel from Dr. David L. Belding, former Biologist for the Massachusetts Department of Fisheries and Game who is now a member of the staff of the Woods Hole Oceanographic Institution.

The Institution has worked in close cooperation with the U. S. Fish and Wildlife Service which is conducting investigations in Essex County and in other parts of New England under a federal appropriation for the improvement of the soft and hard clam fisheries. Members of the Institution served on the Committee of Clam Technicians sponsored by the Atlantic States Marine Fisheries Commission of which Massachusetts is a member.

The Woods Hole Oceanographic Institution wishes to express its appreciation to Mr. Francis W. Sargent, Director of the Division of Marine Fisheries, and to Mr. Charles L. Wheeler, Biologist of the Division for their valuable suggestions and close cooperation.

Alfred C. Redfield
Associate Director
Woods Hole Oceanographic Institution

December 31
1953

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SIXTH REPORT OF INVESTIGATIONS OF THE SHELLFISHERIES OF MASSACHUSETTS *

BY

HARRY J. TURNER, JR.

INTRODUCTION

During the year 1953 the Woods Hole Oceanographic Institution has conducted biological investigations of the sea scallop, the edible crab, the soft clam and the quahaug. The work on the sea scallop has now been terminated with the departure of Mr. Posgay who has left the Institution to conduct an investigation of the striped bass.

The investigation of the sea scallop has revealed several important facts of commercial importance. The rate of growth, which has been accurately determined in the laboratory, has been related to the rate of growth under natural conditions. Growth has been shown to be favored by low temperatures, and inhibited by temperatures above 60° F, and the thermal death point of the scallop has been determined. The spawning period has been determined and some information on the settting habits has been obtained. Tagging experiments and studies of individual populations of sea scallops have provided sufficient information to predict possible increases in expected catch provided the gear is modified to select the older scallops and to release the younger ones.

The investigation of the edible crab, *Cancer irroratus* was undertaken to determine the advisabilty of managing the fishery by closed seasons. The fishermen have noted the seasonal variation of the catch and have been concerned as to whether the fluctuations are due to overfishing or to physiological changes in the crabs that influence catchability. The moulting cycle of the male crab has been determined and evidence has been acquired that indicates that the volume of the commercial catch is in part determined by the moulting cycle.

The investigations of the soft clam have been concerned with methods of management of this fishery by the closure of areas containing dense accumulation of undersized, or "seed" clams. Observations on the Raccoon Island set at Quincy have indicated that natural mortality under crowded conditions may be so great that no benefit and even commercial losses may result from prolonged closure of such areas. Similar conclusions were derived from an analysis of published data on a heavy set on Rowley Reef, Plum Island Sound that occurred in 1906.

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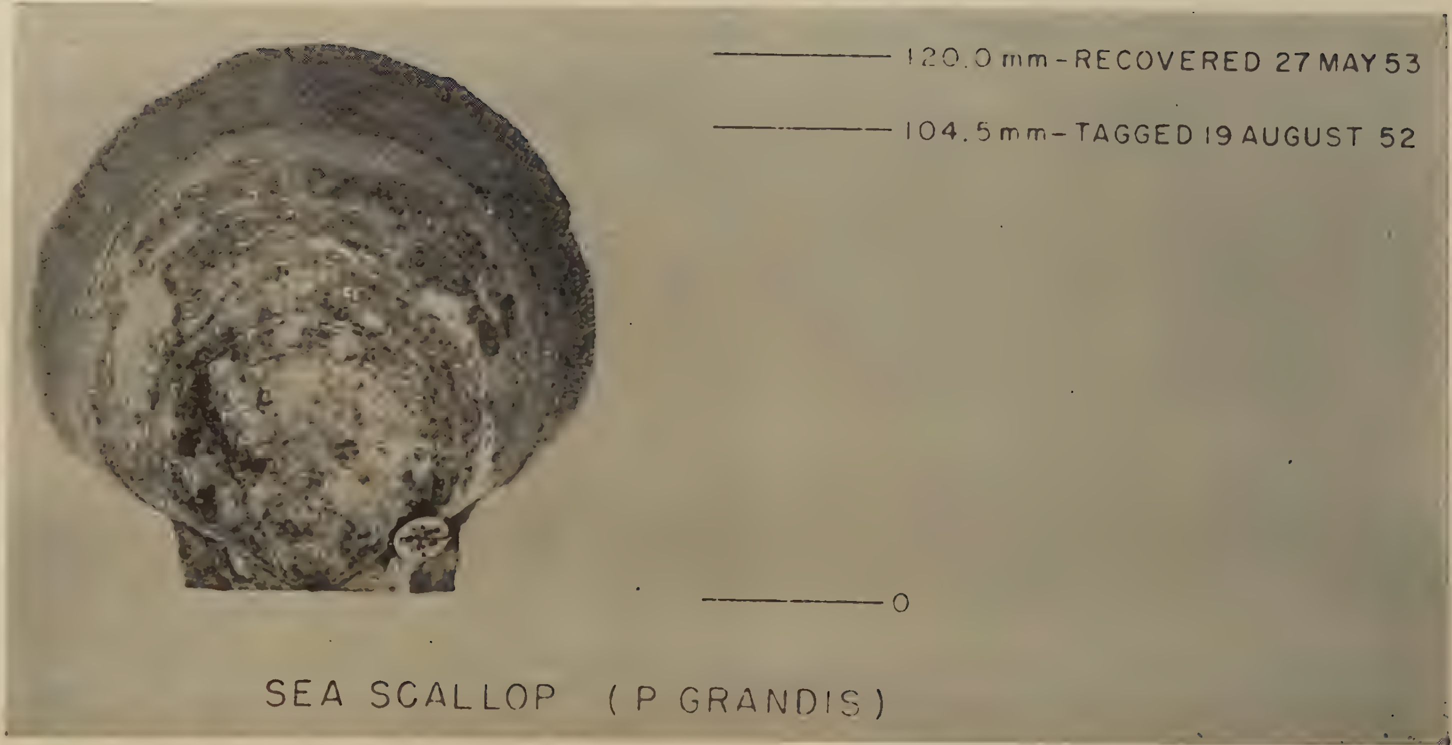
* Contribution No. 715 from the Woods Hole Oceanographic Institution.

The investigations of the quahaug comprised a series of experiments designed to determine if any of the local species of commercial mollusc could be grown in artificial salt-water ponds. Experiments conducted in tanks showed that the quahaug was the only species that would survive and grow without interchange of water. In tanks of stagnant water enriched with fertilizer to stimulate the growth of phytoplankton as food, quahaugs grew at a rate that is comparable to that under average natural conditions. The optimal salinity for growth was determined, and it was found to correspond to that generally prevalent in the lower parts of bays and estuaries where oceanic waters brought in by the flooding tides become somewhat diluted by the fresh-water run-off from the land.

In additions to these papers this report also includes a comprehensive review of advances in the knowledge of the biology of the common commercial molluscs of the East Coast of the United States and Canada. Such a review is essential at this time, since Federal, State and private agencies have conducted such extensive investigations for the past five years that the dissemination of the accumulation of knowledge has lagged far behind its acquisition. Likewise, this information is either unpublished or has been reported in diverse publications, some of the older of which, containing pertinent material, are out of print.


120.0 mm - RECOVERED 27 MAY 53
104.5 mm - TAGGED 19 AUGUST 52
0
SEA SCALLOP (P GRANDIS)

Upper valve of one of the tagged sea scallops showing the tag, the strong check mark that the animal put on it at the time of tagging, and the increase in length during the forty weeks that it was at large.

SEA SCALLOP INVESTIGATIONS

BY

J. A. POSGAY

The New Bedford sea scallop fishermen have recently requested, through the Atlantic States Marine Fisheries Commission, that the U. S. Fish and Wildlife Service set up a program of research on the sea scallop. It seems probable that such a program will be established in the near future if funds become available. This report, which marks the termination of the present investigation into the ecology of the sea scallop, will therefore summarize our present knowledge of the scallop and the scallop fishery and suggest future lines of research.

SPAWNING AND PELAGIC LIFE

The new year class of sea scallops begins life in late summer or early fall when the adults spawn. The exact date of spawning probably varies from year to year and place to place. Spawning has been reported: in the Bay of Fundy during August (Stevenson, 1936), late August to early September (Dickie, 1953); off the Maine coast on August 20 (Drew, 1906); in Cape Cod Bay during late September or early October (Posgay, 1950). On September 15, 1953, a large number of sea scallops were examined in Cape Cod Bay; only one percent, all males, showed any signs of having started to spawn.

The factors which induce spawning in wild populations are obscure. Dickie (1953) believes that it may be related to the tidal cycle; the author believes that it may be associated with the autumnal chilling of the water. Whatever the cause, it seems probable that the males are stimulated first and that the presence of sperm in the water induces the females to shed their eggs. Considering the relatively large distances between individuals, it is difficult to see how a large proportion of eggs could be successfully fertilized unless some such mechanism were involved. Individual scallops which have been observed in the laboratory have shed all their spawn in a series of spasms over a period of a few days. Immediately after each spasm, they closed their shells and did not feed for a few minutes. This would permit the spawn to diffuse away from the immediate vicinity and reduce the chance of the scallop immediately ingesting its own spawn. Careful observation of wild populations coupled with measurement of the physical factors of the environment should give fairly complete answers to these problems.

The fertilized eggs are slightly heavier than sea water and probably remain on the bottom as they segment and develop into the first free-swimming stage, the trochophore. These are ciliated and capable of remaining off the bottom. The next stage, the veliger, is also free-swimming, but both Drew and Stevenson report them as tending to stay close to the bottom. The pelagic stages seem to require about one or two weeks, probably dependent on water temperature, for their completion. Close examination of older animals shows that they were probably about 0.5 mm long when they settled to the bottom.

To the author's knowledge, no one has yet observed any but the first four or five days of this period of the scallop's life. Several investigators have been able to induce spawning in the laboratory and observe the development of the trochophore and the veliger but after this the animals have always died. Loosanoff and his co-workers have successfully carried the larvae of other shellfish through to the setting stage and there seems to be no inherent reason why the same techniques would not work on sea scallop larvae. According to the author's experience, however, a high degree of skill, training, care and even luck is required for its successful completion. Adult scallops are gravid and fully ripe throughout the spring and summer even though no natural spawning occurs. They can be induced to spawn at any time during this period by gradually warming the water to 10-12° C (50-54° F) and then sharply dropping the temperature. A large percentage of the eggs will become fertilized and begin to develop. Our larval cultures apparently failed because of the lack of a proper food supply at the time when feeding first became necessary. A determined attack on this problem should be successful and, once a satisfactory technique has been developed, it should be reasonably simple to determine what environmental factors are critical for the successful production of a newly spawned year class.

The smallest sea scallops that have ever been found were about 2.0 mm (.08 inch) in length. They were collected by Baird (1953) in March from Penobscot Bay. All were found attached by their byssal threads to clumps of the erect, bushy bryozoan *Gemellaria loricata.* The bryozoan colonies with their attached scallops were brought into the laboratory where they continued to grow. They were observed to desert the bryozoan and fasten themselves to bits of broken shell, small stones and the walls of the aquarium when they reached a length of 5 mm (.18 inch). Since it seems unlikely that the newly setting scallops require that their place of attachment be a bryozoan, it should be possible to collect these tiny specimens by placing pieces of frayed rope or some similar material in likely locations shortly after the time of spawning. This would provide material for studying this phase of the scallop's life.

With the exception of the above case, very few scallops under 20 mm (.79 inch) long have been collected. Most scallop fishermen show little knowledge of really small scallops. When they speak of "seed", they almost always mean scallops just under 75 mm (3 inches) in length. Their dredges usually have three inch rings in the bag which, of course, do not catch the smaller animals unless the bag happens to become clogged with trash. Even then, the tiny scallops are so inconspicuous that only a careful search will reveal their presence. Fishermen, naturally, haven't the time or the inclination for such a task although many of them have taken the time to collect samples of small size classes for this author.

Thus, the entire early part of the scallop's life history is almost unknown. It is an interesting and important period which should be thoroughly investigated. These tiny scallops are probably on the menu of every hungry animal that roams the ocean bottom. They have been reported from the stomachs of cod, haddock, skates, and eel-pout. The amount of this predation must be fantastic, but at present we cannot make even a guess at its magnitude.

SETTING AND BED FORMATION

It is probable that it is sometime during this period that the characteristically even-aged scallop beds are formed. The factors which influence these concentrations are unknown. At this stage they are very active swimmers. They frequently sever their byssal threads and take off on flights of considerable length. These flights seem not to be in any way directed. The most plausible theory of bed formation assumes that they are carried about by swift tidal currents until they happen to be deposited in areas of low velocity where they remain. The swimming powers of these small scallops are prodigious; they have been reliably reported on the surface over Georges Bank where the depth exceeded 25 fathoms. The habit of byssal attachment is lost when the animals become about 75 mm (3 inches) long. There is no evidence that sea scallops ever migrate. All of the tagged scallops which have been returned were recovered in almost the exact location where they were released.

A great deal of information about this period of the scallop's life could be obtained by selecting several areas known to produce regular crops of scallops and then dredging at regular intervals shortly after the spawning season with a fine-meshed dredge. Once the newly settled scallops are discovered, they should be closely watched to see how their numbers and concentrations change, how they behave, how fast they grow and how many die or are eaten.

AGE AND GROWTH

For the proper management of any fishery, it is essential to know the age composition of the stocks, the yearly growth rate and the longevity. The utility of this information is perhaps best illustrated by the case of the bay scallop, *P. irradians*. If the bay scallop population of a salt pond is examined in October, one will find that it is quite evidently made up of two distinct size groups. One group is made up of individuals about 55 mm (2.17 inches) long bearing a ridge or ring on the shell. The other group is about 25 mm (1 inch) long and has no ring on the shell. Through the work of Belding (1910) it is known that the smaller animals were spawned the previous June and are thus less than one year old. The larger animals are over one year old with the ring as evidence of having passed through a period of slow growth during the previous winter. Since much larger bay scallops with two rings on their shells are quite uncommon, it is evident that almost all of the larger animals will die during the next fall or winter. These facts are the basis for the regulation of the bay scallop fishery. The taking of the small bay scallops is forbidden since not only will the yield be 6 or 7 times greater if they are allowed to grow for another year but, because none of them will spawn until the next June and few of them live to spawn twice, they are required to provide the next generation. Very few of the larger animals, however, will survive the winter and they should be completely fished out or they will be wasted. Few if any other fisheries are simple enough to have such sensible regulations based upon such well grounded facts.

Three general methods of determining the age and growth rate of sea scallops are available: interpretation of the check marks found on the shells, comparison of length-frequency distributions and the recovery of marked animals.

At the beginning of this investigation it was anticipated that the check marks found on the shells would give a simple method of determining age and growth rate. Stevenson (1935) and Dickie (1951, 1953) have reported successful use of this method on sea scallops from the Bay of Fundy and the Gulf of St. Lawrence. After close examination of many shells, however, it became apparent that sea scallops from our area could not be validly and accurately aged by this method. The Cape Cod Bay sea scallops show such a confusion of check marks that separating the marks that might be caused by some annual event, from those caused by some irregular event, becomes a matter of subjective decision by the investigator. The Georges Bank sea scallops, on the other hand, are generally quite smooth and show few or no check marks.

Enough length-frequency data has now been collected so that it is believed that Figure 2 represents a good estimate of the average growth curve of Cape Cod Bay. In order to illustrate how data of this type is used, a discussion of the method follows.

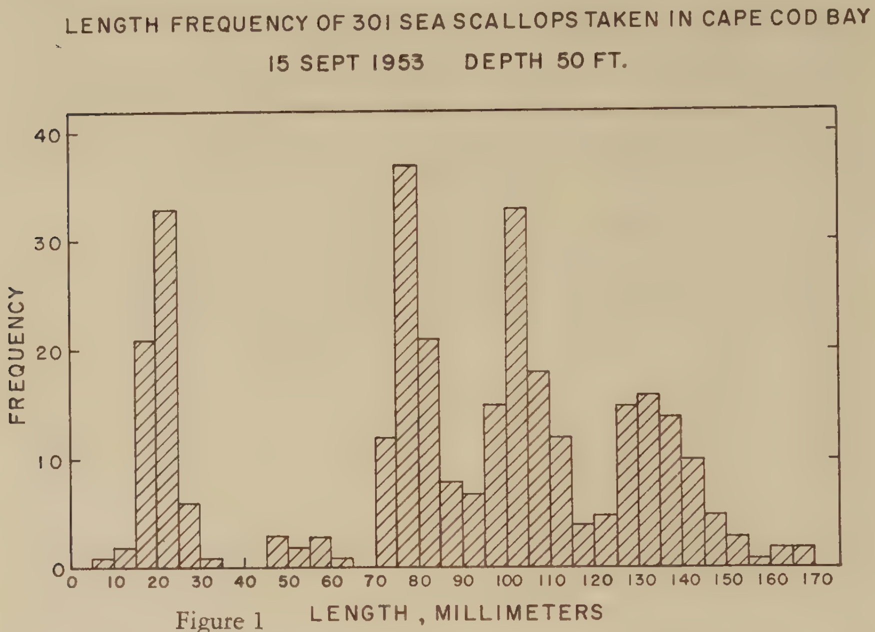
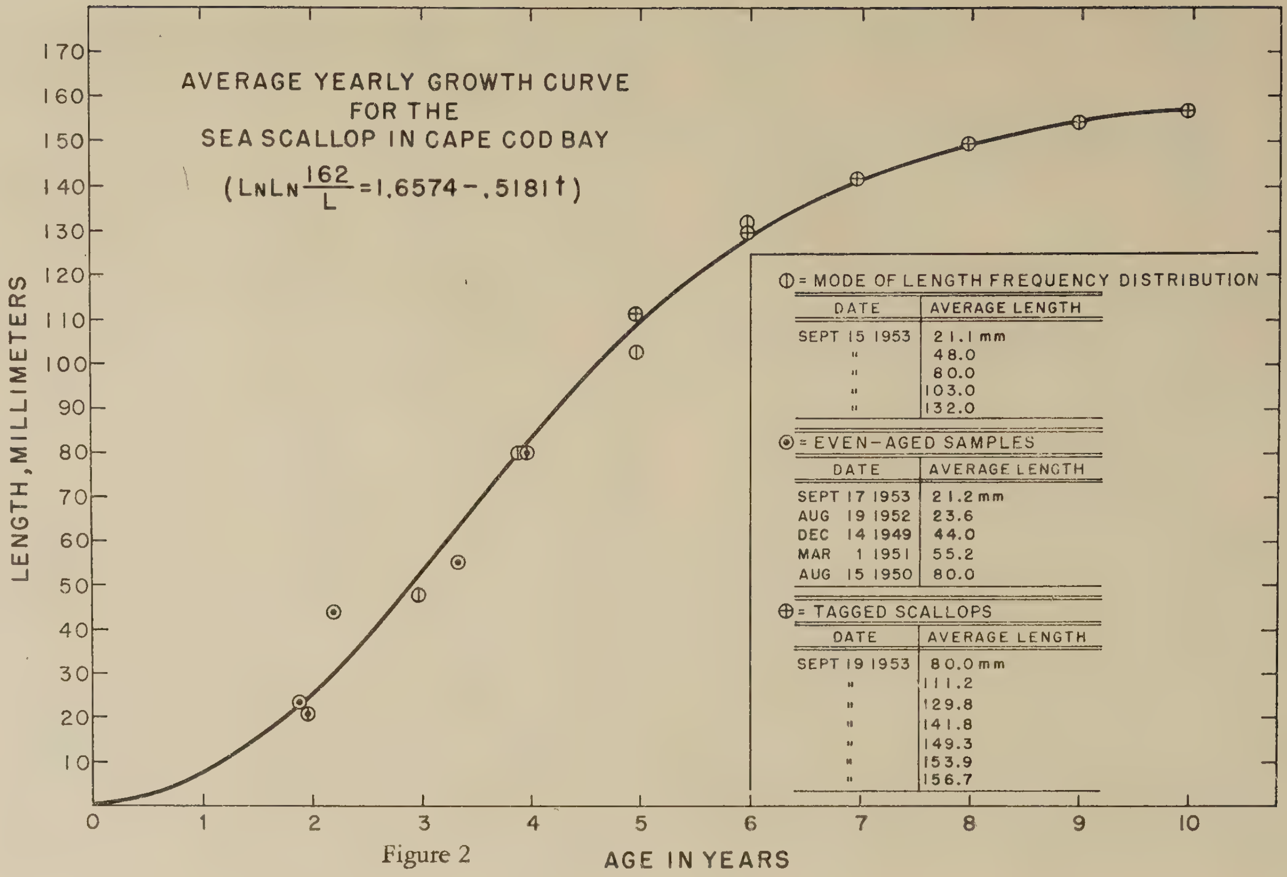


Figure 1

Figure 1 shows the length-frequency histogram obtained by measuring a large sample of sea scallops collected September 15, 1953 in Cape Cod Bay. The particular area from which these animals were taken is known to have been only lightly fished during the past few years. Since it is known that the lengths of any single year class tend to form a normal distribution, it is reasonably safe to assume that each of the peaks of the histogram represents the average size of a separate year class. The weak frequency groups with a peak in the vicinity of 48 mm probably represent a year class that for some reason was unsuccessful in this area. It can also be said that each of the peaks represents the average size of some year class close to the end of some full year of life since it has already been established that late September is the spawning season.

The next step was to assume, since there was no evidence to the contrary, that each of the peaks, 21 mm, 48 mm, 80 mm, 103 mm and 132 mm, represents a successive year class. Therefore, the lengths at which the peaks occur were plotted one year apart on the time diagram of Figure 2. Samples whose range in



⦶ = MODE OF LENGTH FREQUENCY DISTRIBUTION

DATE	AVERAGE LENGTH
SEPT 15 1953	21.1 mm
"	48.0
"	80.0
"	103.0
"	132.0

⊙ = EVEN-AGED SAMPLES

DATE	AVERAGE LENGTH
SEPT 17 1953	21.2 mm
AUG 19 1952	23.6
DEC 14 1949	44.0
MAR 1 1951	55.2
AUG 15 1950	80.0

⊕ = TAGGED SCALLOPS

DATE	AVERAGE LENGTH
SEPT 19 1953	80.0 mm
"	111.2
"	129.8
"	141.8
"	149.3
"	153.9
"	156.7

Figure 2

size was small enough to make it likely that they were all of the same year class had been collected at various times in the past. These were plotted on the graph at the time of year that they were collected and during the year that seemed most reasonable from the evidence of the points plotted previously.

Further evidence of the magnitude of the yearly rate of growth has been drawn from the growth of tagged sea scallops which had been released in Cape Cod Bay. Table 1 shows the data from the tagged scallops. Only Series I, all of which had grown for about ten months, was used to extend the growth curve to the larger sizes. The method by which this was done is shown by the graph in Figure 3. It has been demonstrated by Walford (1946) that plotting the size at age N years against the size at age N + 1 years gives a straight line at sizes above the inflection point of the usual growth curve. Inspection of the points plotted on the time diagram of Figure 2 showed that the inflection point, the place where the shape of the curve changes from concave to convex, fell somewhere between 60 mm and 70 mm (2.5 inches). The amount that each scallop had grown between the time that it was tagged and the time that it was recaptured was extrapolated to a full year and the resulting yearly growth plotted on Figure 3. A straight line was then fitted by the method of least squares. The first year class after the inflection point of Figure 2 had an average size of about 80 mm so, according to Figure 3, it should have an average size of 111.2 mm one year later. Repeating this process gave the average size of succeeding year classes. These points were also plotted on Figure 2. The graph of Figure 3 also gives the maximum attainable size, when a year produces little or no growth, as 162 mm (6.3 inches).

The situation at the lower end of the average yearly growth curve is more difficult and the estimate less precise. A year class is shown at about 25 mm but the age of this year class is uncertain since no samples of scallops smaller than this have been collected in the area. If it is assumed that the growing conditions of Cape Cod Bay and Penobscot Bay are similar, Baird's March sample of 2 mm would suggest that the 25 mm year class is at least two years old and possibly three. With no real evidence either way, this year class was taken as two years old. All the information collected from the length-frequency histogram, the even-aged samples, and the tagged scallops was then averaged by fitting a Gompertz curve to the points by using the method of least squares on the linear form of the equation.

The increase in length with time is a convenient index of growth but the increase in weight of marketable meat is a much more useful piece of information. Figure 4 shows the relationship of the weight of the "eye" to the length of the shell of the sea scallop. The "eye" makes up about 40% of the total weight of the fleshy part of the animal.

EFFECT OF TEMPERATURE ON GROWTH

The growth of any animal is the total result of a great many interacting factors but one of the most important environmental factors which affects the growth of all cold blooded animals is temperature. It is considered a physiological truism that the rate of a metabolic reaction varies directly with the temperature. A in Figure 5 is a generalized expression of this theory; below a certain temperature, nothing happens; as temperature increases, the rate of the reaction increases until heat stupor overcomes the animal and it dies. B, C, E, and F show the

TABLE 1

GROWTH OF TAGGED SEA SCALLOPS IN CAPE COD BAY

SERIES I—Tagged Sept. 19, 1952

Size When Tagged	Size When Recovered	Amount of Growth	Number of Weeks Out
64.0 mm	98.0 mm	34.0 mm	43
69.5	102.0	32.5	43
71.5	93.0	21.5	43
94.5	115.0	20.5	43
104.5	120.0	15.5	40
105.5	126.0	20.5	43
110.5	125.0	14.5	43
117.0	127.0	10.0	46
117.0	136.0	19.0	43
126.0	138.0	12.0	43
SERIES II—Tagged Sept. 16, 1953			
81.0	86.5	5.5	8
82.0	88.0	6.0	8
99.0	102.0	3.0	8
99.0	102.0	3.0	8
102.0	105.0	3.0	8
78.0	85.5	7.5	16
81.0	84.5	3.5	14
101.0	103.5	2.5	16
103.5	107.5	4.5	14
114.0	115.5	1.5	13

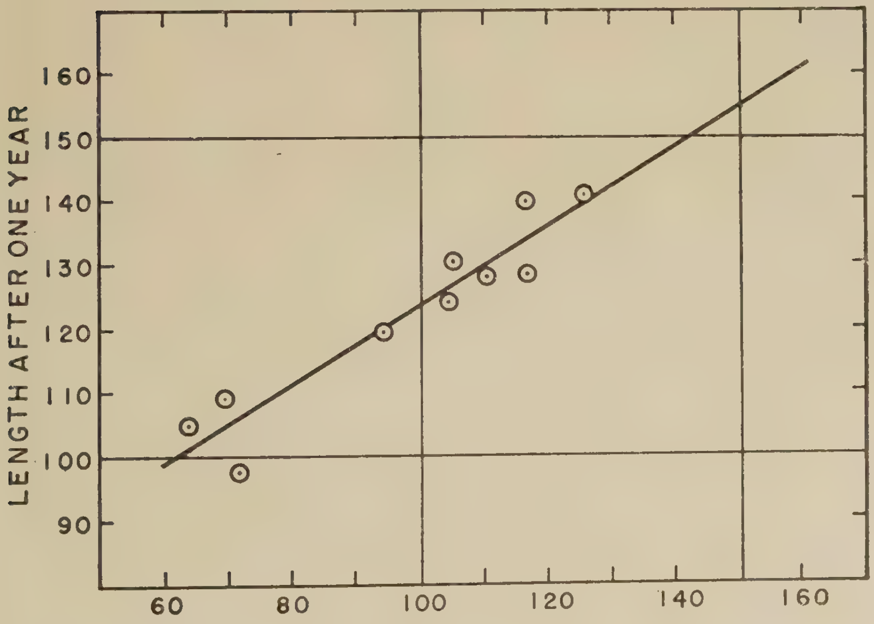


Figure 3

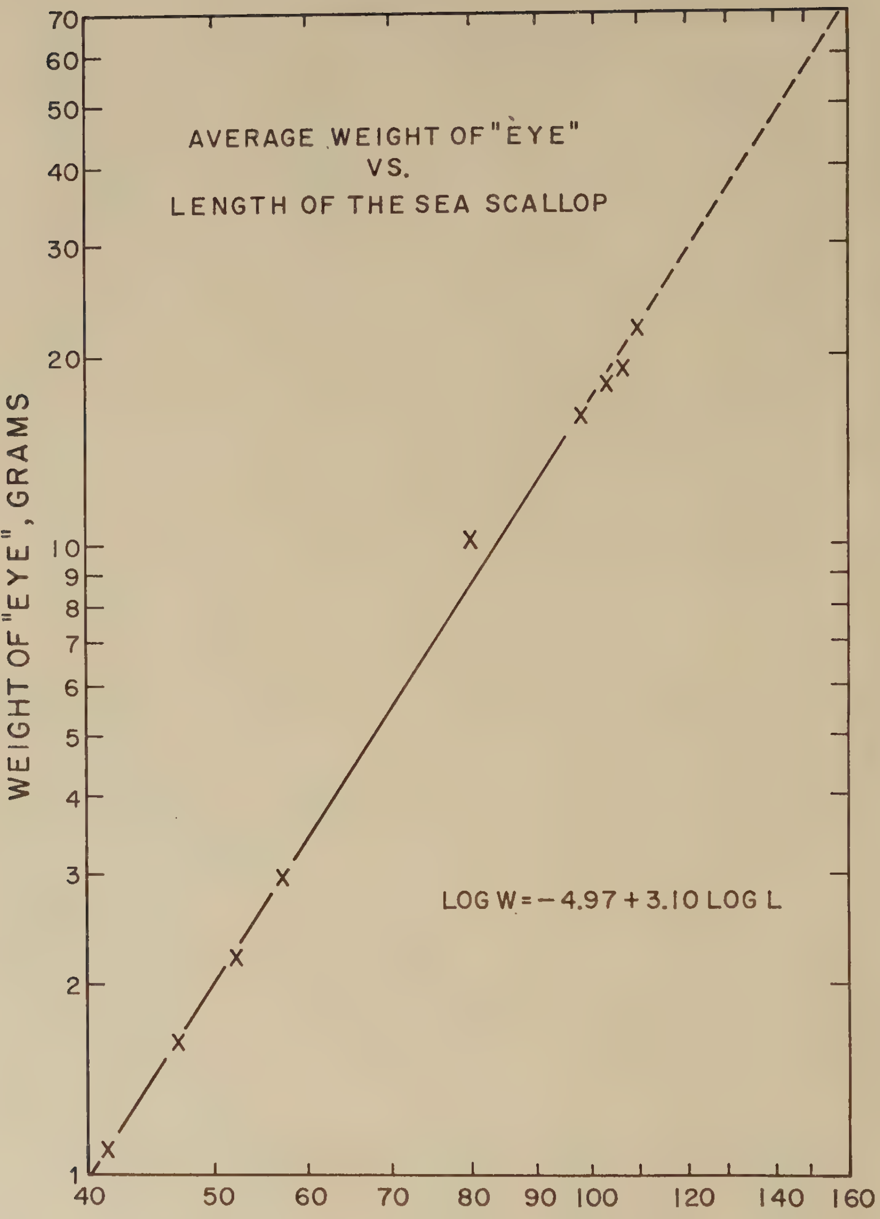
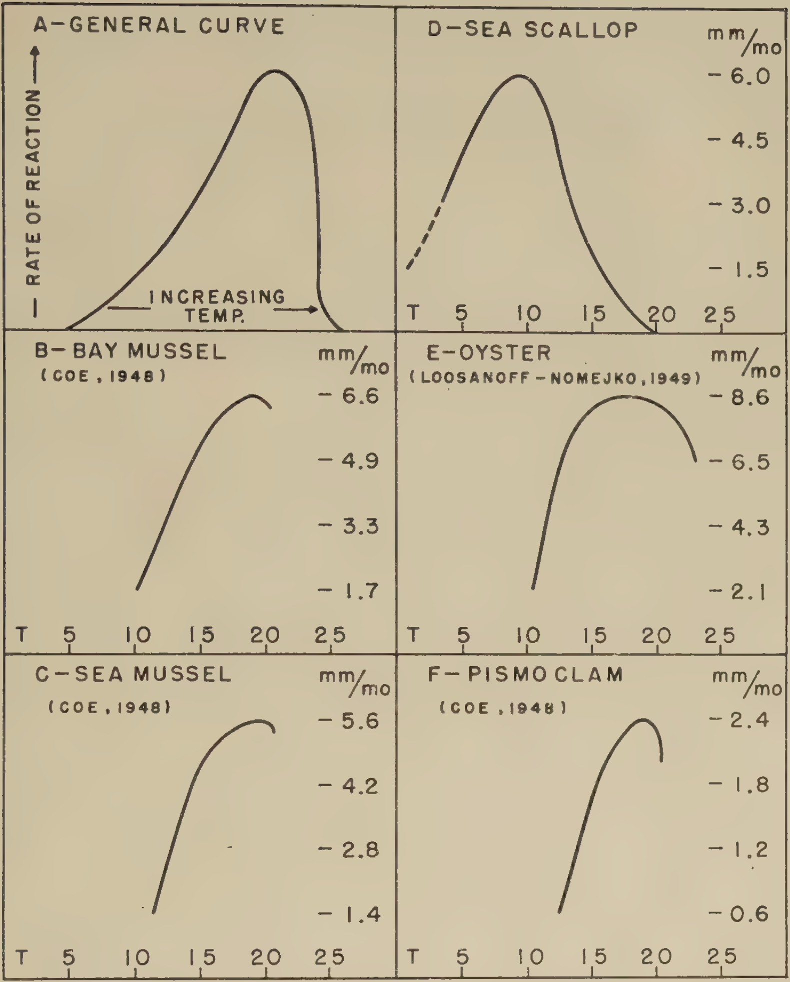


Figure 4 LENGTH IN MILLIMETERS

Figure 5



THE EFFECT OF TEMPERATURE ON GROWTH RATE

effects of temperature on the growth rate of four bivalve mollusks and it will be noticed that they are quite similar to A with the maximum growth rate at about 20°C. The growth of the sea scallop, illustrated in D of Figure 4 has quite a different pattern. It will be noted that the maximum growth rate occurs at about 10°C and declines only gradually at higher or lower temperatures. The dotted portion of this curve, below 3.5°C, is considered a reasonable extrapolation even though there are no experimental data for this area. The sea scallops used in these experiments, all about 45 mm in length, showed no signs of stupor until the temperature approached 20°C. The maximum growth rate of these sea scallops, about 6 mm per month, may be considered a minimum figure, since aquarium life is generally less favorable than the natural environment.

Table 2

YIELD OF THE SEA SCALLOP FISHERY

	TOTAL LANDINGS		TRIPS INTERVIEWED AT NEW BEDFORD			
YEAR	UNITED STATES	NEW BEDFORD	LANDINGS	NUMBER OF TRIPS	DAYS FISHED PER TRIP	CATCH PER BOAT PER DAY
1952	17.1	12.1	12.1	1,393	5.6	1,559 lbs
1951	18.6	12.6	12.5	1,478	5.1	1,658
1950	19.9	12.0	11.6	1,393	5.1	1,646
1949	18.3	11.7	11.2	1,494	5.4	1,389
1948	16.6	10.1	9.5	1,404	5.1	1,320
1947	14.6	10.7	10.5	1,435	4.4	1,669
1946	11.6	8.9	7.6	766	5.5	1,790
1945	5.7	3.9	2.8	296	5.8	1,638
1944	4.9	4.0	3.1	325	5.3	1,807

(millions of pounds) (average)

This growth rate vs. temperature curve provides a basis for calculating the theoretical growth rates of different areas or different years if the yearly temperature curve is known and other factors can be assumed to be equal. An area with a small annual range of temperature near 10° would have a high growth rate while one which was generally colder, warmer or had a large yearly range would have a lower growth rate. On this basis, sea scallops on Georges Bank should grow about 40% faster than those in Cape Cod Bay.

THE YIELD OF THE FISHERY

The yield of the sea scallop fishery, which had been increasing rapidly, has dropped slightly in the last few years. Official U.S. Fish and Wildlife Service figures, taken from Premetz and Snow (1953), are shown in Table 2. This table shows that while total U.S. landings have dropped since 1950, the New Bedford landings have remained about the same. The small difference between the total landings in New Bedford and the total landings of the trips that were interviewed show that the other columns which relate to the effort expended may be regarded as representative of the entire New Bedford fleet. These data for the New Bedford fleet can also be regarded as representing the yield of Georges Bank since almost all New Bedford trips go to Georges Bank and only a few boats from other ports fish on these beds.

The most important feature of this table is the fact that it shows that, while the number of trips per year has quadrupled since 1944, the catch per boat per day has remained almost the same. This fact implies that during this period there has been no decline in the availability of sea scallops on the beds. This conclusion can only be true if there has been no improvement in fishing efficiency. Many scallop fishermen contend that fishing efficiency has improved since the war and that in addition the table does not show a drastic decline in catch per unit of effort which has occurred during 1953. For the purpose of the following analysis we will accept these claims as valid.

It has been the common experience of expanding fisheries that as the number of boats engaged in the fishery increases, the catch per unit of effort remains fairly level. If the fleet continues to expand, the catch per unit of effort starts to drop even though total landings may remain high for a time. Later, the total landings will drop until they level off at some lower figure. Along with this generalized pattern, there is usually a constant drop in the size of the animals being caught until this figure also levels off at a size which is close to the minimum catchable size for the gear in use.

The problem in a fishery of this type is to fix the size of the fish taken at the level which will permit the stocks to maintain themselves and at the same time give the highest possible long-term yield to the fishery. If this problem is to be solved positively, it is necessary to know the total weight of the stock, the starting catchable stock, the catchable stock at the end of the year, the number of animals that attain catchable size during the year, the growth rate of each year class, the natural mortality, and the year's total catch (Russell, 1931). No fishery has ever been studied completely enough to give the magnitude of all these factors but certain conditions of the sea scallop fishery permit an estimate of the effect of fishing different size classes.

The first of these conditions is that the size of scallop caught is a direct result of the size ring used in the dredge bag. Medcof (1952) has compared the catch of dredges with 2 5/8″ rings to the catch of dredges with other size rings. The catches were divided into two groups, those scallops over 4″ and those less than 4″, since Canada has a 4″ minimum size law. His results show that a dredge with 3 1/2″ rings will reduce the catch of sub-legal scallops by 72% while only reducing the catch of legal scallops by 5%. This evidence shows that it is possible to fix the minimum catchable size at any level by using a ring 1/2″ less in diameter.

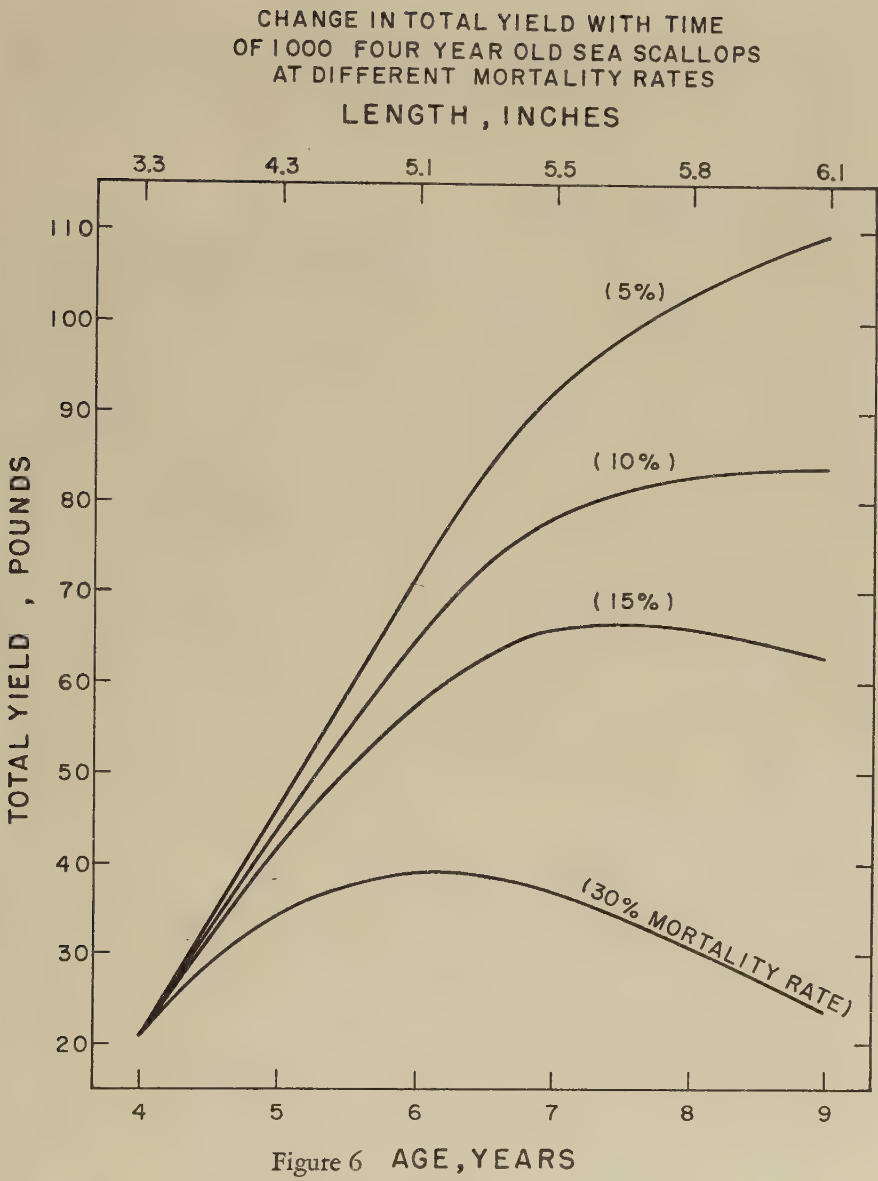
An estimate of the natural mortality is necessary before the effect of fishing at various levels of size can be estimated. We have no such figure for Georges Bank but Dickie (1953) has estimated 10% per year as an average mortality for all catchable sizes on the Digby beds. The average yearly growth rate and the increase in weight per year are known for Cape Cod Bay and these rates for Georges Bank should be as good if not better. No estimate of the yearly recruitment can be made but since all that we are going to do is assess the effect of fishing any single year class at different ages, it can be neglected.

Since 10% per year is only a crude approximation of natural mortality, the effect on yield of fishing at different ages has been calculated for several different mortality rates. Figure 6 gives the results of these calculations based upon a hypothetical population of 1000 four year old scallops. A study of these curves leads to some interesting conclusions. New Bedford sea scallopers fishing on Georges Bank during 1952 landed an average of 8,700 pounds of meats per trip (Premetz and Snow, 1953). Although the average size of the scallops being caught at that time is unknown, it can be estimated if we accept the fishermen's claim of a decline in catch per unit of effort. As mentioned above, in a heavily fished stock the average size of the individuals caught declines constantly until it levels off at some size which is the minimum catchable size for the gear being used. At this point, the accumulated stocks of old, large animals have been removed and the annual yield of the fishery cannot exceed the number of animals which during the year grow large enough to be caught. This is generally the time when fishermen begin to complain of "depletion" since the fleet has usually expanded beyond the ability of the stocks to support it in the style to which it has become accustomed.

Since the New Bedford scallop fleet is presently complaining of bad times, it can be assumed that they are now fishing the minimum catchable size. For the type of dredge which they use, this is the four year old class which averages about 3.3 inches in length.

It requires about 410,000 four year old scallops to yield 8,700 pounds of meats. At a mortality rate of 30% per year (triple the best available estimate) there would be 204,000 of them left if they were undisturbed for two more years. If they grew at the same rate as the Cape Cod Bay stocks, they would be 5.1 inches long and would yield about 16,500 pounds of meats. To land this larger quantity would require the same amount of steaming time and dredging time but only half the shucking time and the yield would be almost doubled. The yield would of course be still greater if the estimate of the mortality rate proved to be too high or if the growth rate were higher.

Fishermen are only human and few, if any, of them are willing to restrict their own efforts and perhaps take a temporary loss for what may prove to be the benefit of others and not themselves. In justice, it must be said that many fishermen cannot afford to take even a temporary loss. Already on the edge of



CHANGE IN TOTAL YIELD WITH TIME OF 1000 FOUR YEAR OLD SEA SCALLOPS AT DIFFERENT MORTALITY RATES

Figure 6

bankruptcy, any further loss is likely to spell complete ruin. Therefore, the only way to achieve the benefits to be derived from giving the scallops a chance to grow up is by regulation, either self-administered or imposed from without. The rule for one must be the rule for all. Fortunately there is a simple and effective method of enforcing a minimum size rule on sea scallops by regulating the size of the rings used in the bag of the dredge.

The figures used in calculating the above estimate of the optimal yield are admittedly very crude approximations but they are the best that we have. We have no idea of the size of the stocks, their distribution and density, the numbers removed by fishing, the natural mortality of each year class, the actual growth rate or the yearly recruitment on Georges Bank.

DISTRIBUTION AND DENSITY

The central problem which should be investigated if there are to be any answers to the above questions is that of the distribution and density of all bottom-dwelling animals on Georges Bank. This community is of interest not only because one of its constituents, the sea scallop, is of direct economic importance but also because it forms the major food supply of the vast hordes of groundfish which are the basis of the New England trawler fleet.

As far as the sea scallop is concerned, one of the limiting factors of its distribution has been determined experimentally. The usual barrier to the spread of essentially Arctic animals like the sea scallop is the height of the maximum summer temperature. This figure has been observed to vary with the age of the scallops concerned. Those under two inches in length are more resistant to the lethal effects of high temperature than those over three inches. In the larger animals, the signs of heat stupor: gaping shell, retracted mantle and sluggish reactions, are first seen as the temperature rises above 15°C. As the temperature rises, more and more animals die. None survive even short exposure to water whose temperature is over 20°C. The smaller animals do not show the effects of heat stupor until the water temperature exceeds 20°C and many of them survive at a temperature of 23°. Over 23°C, mortality is complete. From these observations, it appears that no area in which summer temperatures exceed 20°C (68°F) can produce a crop of marketable sized sea scallops. This, however, only gives a very general limit to the distribution of the animal. It still does not explain the fact that scallop beds are evidently scattered in a spotty manner over Georges Bank, an area which so far as we know seems to be everywhere suitable.

The towed dredge has been the standard tool for investigating the distribution of bottom-dwelling animals but it is really only useful for either rough qualitative work or the collection of actual specimens for identification. Aqua-Lung divers were sent down to examine an area that had just been dredged over with a scallop dredge. The dredge had caught an average of one scallop per hundred square yards. The divers' estimate was one scallop every square yard. Thus, the dredge was only 1% efficient. There is another type of dredge available which takes a known bite out of the bottom and brings it to the surface, but to survey an area as large as Georges Bank by this method would be prohibitively expensive.

The search for a tool which was capable of collecting accurate quantitative data at reasonable cost led to the consideration of underwater cameras. Many people have worked with underwater cameras over the last sixty years but it was not until 1940 that Ewing and his co-workers at the Woods Hole Oceanographic Institution succeeded in developing an instrument which showed promise of being a useful scientific tool. Several trials were made over the scallop beds using one of the original Ewing cameras but it did not prove satisfactory.

From the experience gained with this camera, however, we were able to see that the idea was sound and decide what improvements were necessary. Through the co-operation of many people who had worked with and thought about underwater cameras during the last ten years, it was possible to design and build a much improved model. This new camera will do about ten times as much work in the same time as the camera that we used originally. In addition, the pictures are better lighted, sharper, and easier to process.

This camera was recently put through its first tests on Georges Bank. It proved to be extremely reliable and capable of photographing large areas of the

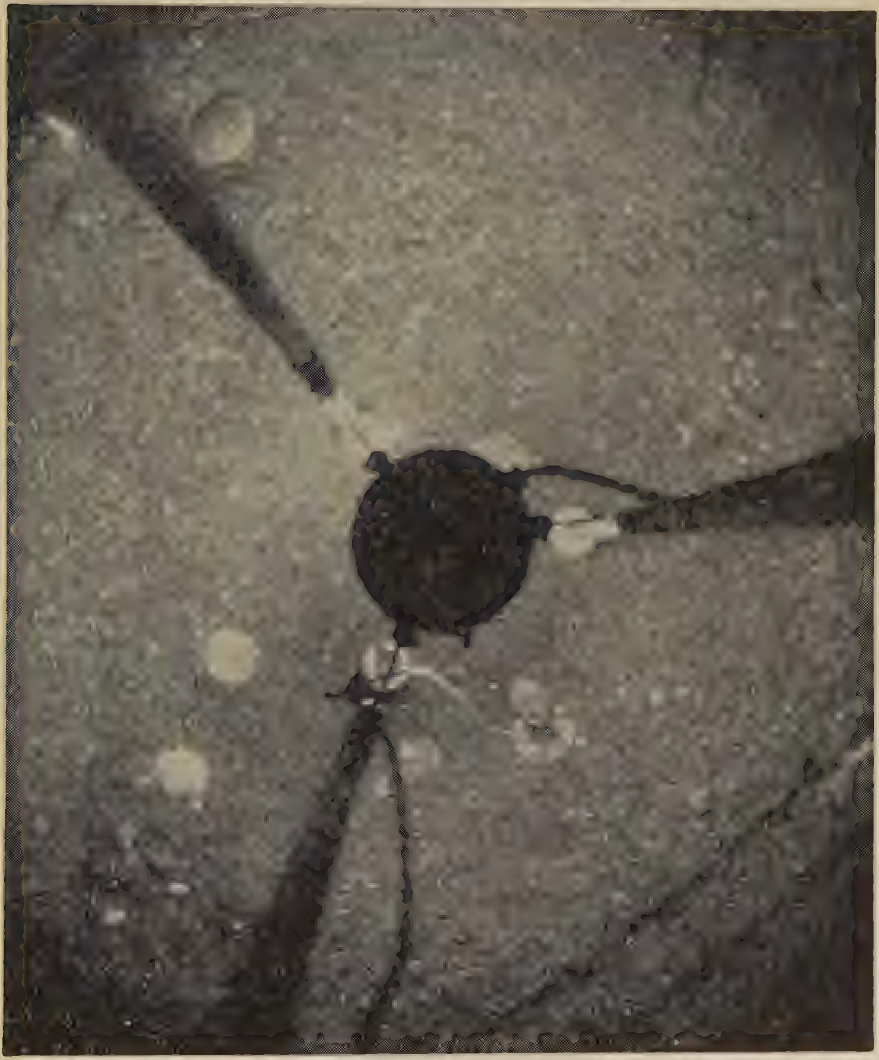


Figure 7. Underwater photograph taken on the Northern Edge of Georges Bank in 35 fathoms of water. The black disc in the center of the picture and the three radiating lines are parts of the structure of the camera. Two live sea scallops are visible in the upper left and a hake about a foot long in the upper right. The visible area totals about forty square feet.

bottom in a short time. On one station, fifty-five pictures, each including forty square feet, were taken in an hour and a half. One of these underwater photographs is shown in Figure 7. Limitations of funds, personnel, and time have prevented the full exploitation of this new tool, but it is hoped that the equipment will be extensively used in the near future to answer many questions about the sea scallop and other bottom populations.

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THE EDIBLE CRAB FISHERY OF MASSACHUSETTS

BY

HARRY J. TURNER, JR.

The mud crab, *Cancer irroratus,* is the principal species of edible crab in the coastal waters of Massachusetts. Its range extends from Nova Scotia to Florida so that it may live in any suitable environment along the entire coast of Massachusetts. The rock crab, *Cancer borealis,* is occasionally used but is not greatly favored by fishermen because of the small yield of meat. The blue crab, *Callinectes sapidus,* an important southern species, normally ranges only as far north as the southern shore of Cape Cod with occasional stray specimens in Cape Cod Bay and Boston Bay. It is occasionally caught within its range in Massachusetts for household consumption. The present investigation has been limited to the mud crab, which is the only species of commercial importance in Massachusetts.

HISTORICAL RESUME

The commercial crab fishery of Massachusetts began around 1900. At that time the method of fishing consisted of lowering circular nets containing bait into the water and pulling them up at intervals. The crabs thus caught were boiled and peddled around the wharves of Boston by pushcart vendors. About 1905 a few enterprising fishermen experimented with various styles of traps and found that something similar to the conventional lobster pot was quite satisfactory. The newly devised traps were so efficient that the pushcart market was inadequate to handle the potential catch, so that out of necessity, the little industry looked for other outlets. It was soon found that hotels and restaurants would readily accept the product if provided in the form of crab meat rather than whole crabs. This problem was easily solved by developing methods of picking out the meats on a large scale. The market continued to expand so that by the late twenties the annual catch exceeded 8,000,000 crabs yielding over 200,000 pounds of meat worth nearly $150,000. The principal center was Boston but small fisheries also existed in Beverly, Lynn, and Gloucester. There were 26 fishermen regularly employed in crab fishing in 1930 with about an equal number fishing intermittently. Small numbers of crabs also were marketed as an incidental part of the catch of the lobster fishery.

Apparently 1930 was not a particularly good year for crabs. Records for the previous years are not now available, but the testimony of the fishermen recorded in 1930 indicated a 2/5 reduction in the catch although there was no diminution of fishing effort. Overfishing was believed to be the cause, and a number of remedies were suggested. Several dealers suggested that a closed season should be imposed from December to April, since the crabs taken during this period were either soft-shelled or hollow, and it was estimated that it took at least 80 crabs to produce a pound of meat. No immediate legislative action was taken.

The annual catch remained relatively constant until 1934 when it fell to a low of a little over 1,000,000 crabs. The drop was apparently caused by a reduction in the number of fishermen and there is no evidence that the availability of crabs had anything to do with it. The following year the number of fishermen more than tripled and the catch rose to more than 7,000,000 crabs. The increased competition brought about some concern for the future of the industry amongst fishermen and dealers who again began to agitate for a closed season. As a result a bill prohibiting the taking of edible crabs between January 1 and March 31 was passed by the General Court in 1937 to take effect in 1938. There were no significant changes in the industry until 1951 when the closed season was extended by law to include the months of December and April.

The request for the extension of the closed season came from certain dealers and owners of meat-picking establishments. Dealers in live crabs whose principal market was outside Massachusetts found that crabs caught in the early spring would not stand shipment and the yield of meat was insufficient to satisfy their customers. These dealers allied themselves with owners of certain meat-picking establishments to request legislation to extend the closed season in the hope that the crabs ordinarily caught in April would be preserved until later when the meat content increased. The legislation was opposed by other dealers who maintained that the meat content was satisfactory for their purposes in April when crabs could be caught in greatest abundance. This group maintained such opposition to the extended closed season that in 1953 the Division of Marine Fisheries requested an investigation of the edible crab to determine how the fishery might best be regulated.

LIFE HISTORY

There appears to be no literature on the life history of the edible crab of Massachusetts, *Cancer irroratus*. The large dungeness crab, a related species found in the Pacific, has been investigated to some extent, and the southern blue crab has been intensively studied. However, there is a general pattern common to all crabs. Males mature when they reach their maximal size at the final moult. This generally occurs some time before the female moulting season so that by the time the females moult the males will have hard shells. As the female moulting season approaches, the males hunt out the females and in many species the male will carry the female about with him for some time until she moults. Mating occurs as soon as the female moults and the eggs appear sometime later as a spongy mass which adheres to the appendages of the abdominal segments. The female carries the eggs through their developmental stages and in some species make well defined migrations to definite hatching grounds. The eggs hatch as tiny shrimp-like larvae known as zoeae which drift about in the water currents for varying periods of time. After one or more moults the zoeae are transformed into a different kind of larvae known as megalops. The megalops moults a number of times and finally metamorphoses into a minature replica of the adult crab. In most species of crabs the young moult a number of times during the first year but as they mature there is a tendency for moulting to become an annual event. If there is a definite hatching ground away from the habitat of the adults, the young perform a return migration as they grow. Some species of crabs attain a maximal size and the males mate only once. Others become sexually mature before the maximal size is reached and carry out their reproductive functions a number of times. The number of eggs produced at any one time varies from species to species, generally running from the hundreds of thousands to millions per female. As in the case of all organisms that produce such huge numbers of eggs with a free-swimming early stage, successful propagation depends on so many environmental factors that above certain limits the size of the parent stock is of little importance.

ABUNDANCE OF CRABS AND FISHING

The primary aim of the investigations of the edible crab fishery of Massachusetts was to determine changes in the availability of the crabs throughout the year, to estimate to what extent these changes were influenced by fishing and to what extent fishing might affect future trends in abundances. For reasons of commercial interest records were made of changes in the meat content. Incidental information that might lead to a better understanding of the life history of the edible crab was noted at all times.

The effect of fishing on availability was checked by comparing the catch obtained early in April in two experimental fishing expeditions with that obtained in May when the season opened. The primary object was to see if the crabs would be as plentiful in May as they were in April due to protection by the closed season. The results shown in Table 1 clearly show that crabs were only available in about half the number when the season opened as they had been the month before. The soft conditions of the crabs caught in early April and their relatively low meat content shown in Table 1 indicated that they had recently moulted. The large increase in meat content that took place before May could only have occurred as a result of an enormous food intake by the crabs. It thus appeared that post-moult crabs, in search of additional food required for internal growth are more strongly attracted to bait than later when internal growth is completed. It was thus evident that the initial decline in availability of the crabs was caused by changes in their behaviour rather than in their numbers

TABLE 1

	Daily catch per trap	Crabs per lb. meat	Average meat yield of daily catch per trap
April*	125-150	35-38	Nearly 4 lb.
May	50-75	19-21	Over 3 lb.
June	35-50	19-21	Over 2 lb.
July	35-50	26**	Under 2 lb.
Aug.	20-40	30**	About 1 lb.
Sept.	20-40	30**	About 1 lb.
Oct.	20-40	33**	Under 1 lb.
Nov.	30-50	40	About 1 lb.

* Experimental fishing

** Increase in small crabs in catch

The unit catch continued to decline through June and July to such an extent that the average daily meat yield per trap decreased in spite of the fullness of the crabs. In July the average size of the crabs began to fall off noticeably with further reduction in the meat yield. Both the catch and the yield continued to be poor until the end of November. With the arrival of the moulting season at the end of November the unit catch improved materially but the extreme poor condition of the new post-moults more than offset the advantage (Table 1).

The increase in the unit catch with the arrival of the moulting season gave added support to the original supposition that post-moult crabs are more easilv trapped than those in the hard condition. The relative influence of this factor in relation to the absolute abundance of crabs, other changes in behaviour associated with the seasonal pattern, migrations, etc. cannot be accurately determined without further study. The relative magnitudes of the meat content and availability in April and May make that portion of the season the most productive of crab meat. To date there is little indication that the subsequent decline is due to fishing but rather a result of a change in the response of the hard crabs to baited traps.

RELATIONSHIP OF THE BIOLOGY TO MANAGEMENT

Two unique features in the biology of the edible crab bring out problems in the management of the fishery that differ from those associated with most fisheries. The female is too small to be processed efficiently so that there is no real incentive for the fishermen to bring them to the dock. For this reason the number of reproductive individuals in the total stock is not influenced by fishing, and the recruitment of future generations is assured. The present law which protects the females merely eliminates careless fishing practices. The male crab, unlike the lobster, does not grow beyond a certain size and thus requires no protection after maturity. Consequently there is no indication that commercial fishing as currently practiced will affect the stocks adversely from the long term point of view.

GROWTH AND SURVIVAL OF SOFT CLAMS IN DENSELY POPULATED AREAS

BY

HARRY J. TURNER, JR.

A heavy set of clams that occurred in the vicinity of Raccoon Island, Hough's Neck, Quincy in 1951 contained enough 2-inch clams by the fall of 1953 to permit the area to be opened for commercial exploitation. The opening date was much earlier than was thought to be desirable at the time because only 11% of the clams exceeded the two-inch legal minimal size. However, the scarcity of clams throughout the rest of the Quincy area made it necessary to permit digging prematurely in the Raccoon Island region to alleviate the hardships of the local diggers. A close examination of the data pertaining to this set has now shown that the early opening was not as undesirable as had been formerly supposed since natural destruction was removing the clams faster than their volume was being increased by growth. A similar trend in the Rowley Reef set of 1906, reported by Belding, suggests that this condition may occur in densely populated areas with sufficient frequency to alter the present concepts pertaining to the management of such areas.

The Raccoon Island set was discovered in August, 1951. It was situated along the lower level of Manet Beach, Hough's Neck, Quincy, on a wide strip running parallel to the beach. The entire area, comprising approximately 16 acres, was uniformly populated with 3/8 inch clams in a density of approximately 10,000 per square foot. These clams were situated just under the surface of the mud and occupied practically all of the available space. Likewise, clumps of seaweed scattered about the area were heavily covered with tiny clams that had attached with the byssus.

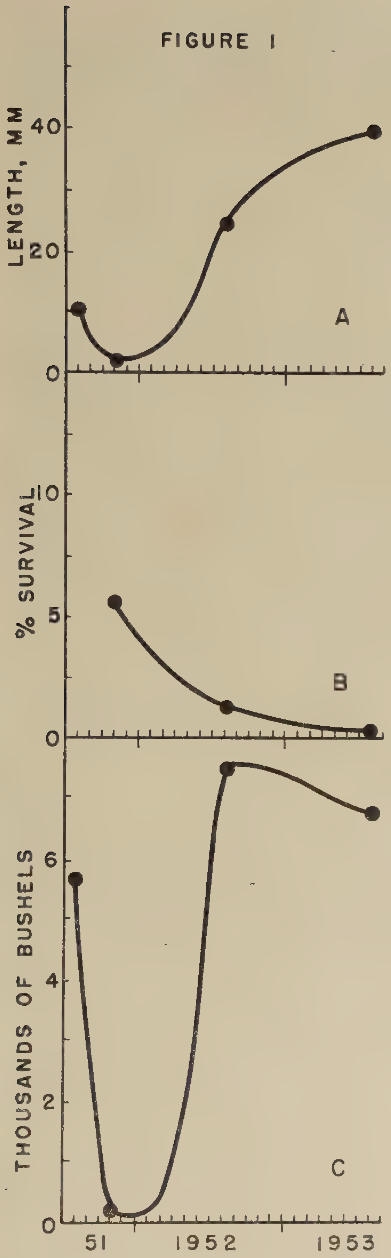
When the area was re-examined in November 1951, the populated area had been reduced to 5 acres, in which the density ranged from 2,000 per square foot along the landward border to 1,600 at the seaward side. A number of samples lumped together showed that the over-all average was 1,800 clams per square foot. The most striking change that had occurred was a marked reduction in the average size of the surviving clams, which was no more than ¼ inch. Extensive accumulations of paired shells of half inch clams on the steep slope of the gravel beach near the high tide mark clearly indicated that the larger clams had been selectively removed from their original location and washed up on the beach. The conditions at that time were described in Woods Hole Oceanographic Institution report for 1951.

An examination of the area in August 1952 revealed that the entire population had disappeared from its original site. However, a four-acre plot along the gravel beach just below the mid-tide mark contained one-inch clams in densities averaging 400 per square foot. This area had been unpopulated the previous November. It was concluded, therefore, that the one-inch clams were the survivors of the original set along the low water mark that had been transported shoreward by the action of the waves. A complete description of the conditions and a hypothesis explaining the change in locality of the population were given in the Woods Hole Oceanographic Institution report for 1952.

By August 1953 the shellfish diggers of Quincy had exhausted most of the available clam areas and requested the local shellfish officer to permit commercial digging in the Raccoon Island area. The set was examined and found to extend over the same four acres as the previous year. The average length of the clams was just over 1½ inches although the distribution of sizes was such that approximately 11% exceeded the two-inch minimal legal length. The density averaged 100 clams per square foot. This number of legal clams of which about 11 per square foot were of legal size was above average for most of the commercial areas of Boston Harbor which made the area very attractive to the local diggers. The possible fate of the 89% undersized clams with their future possibilities was kept in the background by prospects of a small immediate crop to satisfy the demands of the diggers. The diggers justified their demands on the grounds that the clams were dying off so fast that they would be all gone before the majority would have reached a length of two inches. Evidently this idea was based on subjective judgment of the diggers influenced by their immediate need for new areas. Under more favorable conditions diggers would have probably been strongly opposed to opening of areas "loaded with seed" and might even have requested the closure of other heavily seeded open areas.

The data derived from observations on the Raccoon Island set showed that the magnitude of the mortality rates under the conditions prevailing at the time and locality was so great that conventional ideas of conservation did not apply. Additional information recorded by Belding on the Rowley Reef set of 1906 indicates a similar situation. Restrictions that prolong the length of time that shellfish remain in the beds are justified, provided that the practice causes the total volume of shellfish to increase. This situation depends on the relationship of the growth rate to the death rate. As long as the shellfish are growing fast enough to overbalance the quantity removed from the population by death, it is advantageous to delay the harvest. When the two factors reach equilibrium the advantage disappears, and if the relationships become reversed, any delay in harvesting results in losses. Application of this principle is complicated in practice because the relative magnitudes of the factors are either poorly known or more often completely obscured.

The growth rate of the clams of the Raccoon Island set is graphically illustrated in Figure 1A. The rate is essentially similar to average rates determined for various accumulations of soft clams in the Boston Harbor area. The peculiar reduction in length between August 1951 and November 1951 is the result of selective mortality of the larger sizes previously mentioned. The most rapid growth period occurred during the spring and summer of 1952 when the clams attained an average length of 25 mm (one inch) by August 1952. Subsequently the growth slowed down so that by August 1953 the average length was 40 mm (1 9/16 inches). The shape of the curve and experience with other populations make it possible to predict that it would have required at least part of another growing season to bring the average length to two inches.



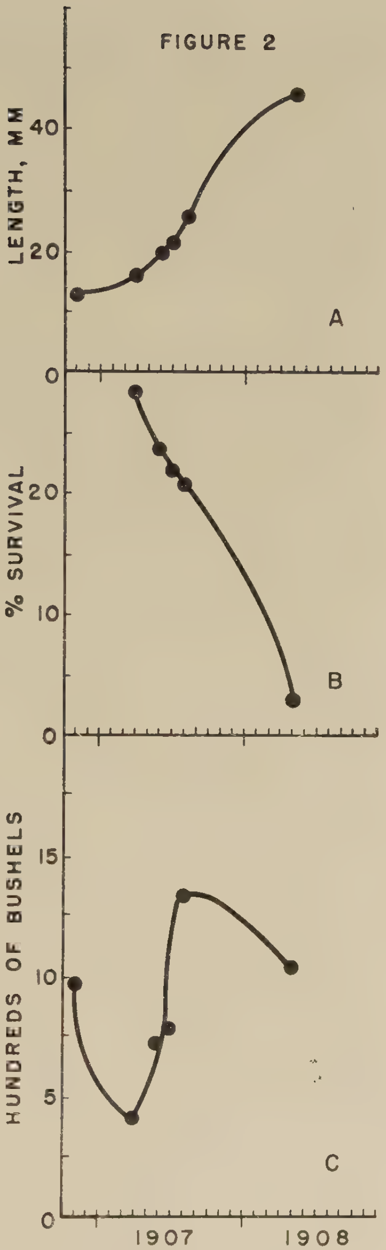


Figure 1. Graphs of the growth, survival, and changes in the volume of the clams in the Raccoon Island set.

Figure 2. Graphs of the growth, survival, and changes in volume of the clams in the Rowley Reef set.

Thus, on the basis of the growth rate alone, it would have been considered advisable to keep the area closed until June or July 1954. It is necessary to point out that the spread in sizes either side of the average, increased as the clams grew so that by August 1953 approximately 11% of the clams were two inches or more in length.

The survival rate illustrated in Figure 1B indicates a trend that appears to justify the fears of the clam diggers. The greatest mortality occurred during the first three months with a survival of only 6% of the original number. In one year, all but 1.04% of the clams had died, and after two years only 0.26% were alive.

Figure 1C indicates the changes in volume that resulted from the antagonistic reactions of growth and mortality. During the first three months of life the mortality of the larger clams of the set reduced the volume to a critically low figure. During the next growing season the rapid growth was sufficient to overbalance the mortality and the volume reached a peak in August when the clams were about one inch long. Then, as growth slowed down, the trend became reversed so that by August 1953 there were fewer bushels of 1 9/16 inch clams than there had been in August 1952 when they were one inch long. In view of the fact that the trend in the volume was downward, it appears that there was some justification for permitting the set to be exploited in August 1953, since the direction of curves of the growth and survival rates indicates clearly that the volume could never be any greater and might even drop to a much lower value. The possible beneficial effects of digging will be discussed later.

It is of interest to compare the history of the Raccoon Island set with that of the Rowley Reef set to show that the situation is not unique. The Rowley set, discovered by Belding in Plum Island Sound in November 1906, extended over a plot of a little more than an acre. The clams were 13 mm long (½ inch) at the time of the discovery and numbered nearly 2,000 to the square foot. By April 1907 the clams had grown to a length of 16 mm (⅝ inch) but had been reduced in numbers to 550 per square foot. By August 1907 the clams averaged 26 mm (just over an inch) in length and numbered 400 to the square foot. The last reported observation was made the following May (1908). The clams then averaged 46 mm (1 13/16 inches) and had been reduced in numbers to 53 per square foot. No data is given on the assortment of sizes but it is safe to assume that by this time about 20% of the clams would have been at least two inches long.

The growth rate of the clams in the Rowley Reef set is given in Figure 2A. It is essentially similar to that of the Raccoon Island set. It does not show an early decline in length and the relatively large size of the clams in November does not indicate that it had occurred. The growth rate of the Rowley Reef clams was slightly lower than that of the Raccoon Island clams but the initial advantage of a greater length in the late fall brought the average of the Rowley Reef clams to a little over an inch by August 1907. Subsequent growth of the Rowley Reef clams was a little greater than that of the Raccoon Island clams, and they attained the length of 46 mm by the following May. Since the growing season had just started at this time it is highly probable that the average would have surpassed the 50 mm (2 inch) mark by August.

The survival rate depicted in graph Figure 2B differs considerably from that of the Raccoon Island set. However, the absence of data for the August-

November period may have obscured an initial mortality similar to that of the Raccoon Island set so that its curve in Figure 2B may actually resemble that of the Raccoon Island set in Figure 1B but with an expanded scale. The essential point demonstrated by the graph is that the survival trend is downward.

Figure 2C depiciting the changes in volume of the clams of the Rowley Reef set bears a striking resemblance to that of the Raccoon Island set. There is an initial decline during the first fall when mortality overbalances the gain in growth. The situation is reversed during the next growing season and the clams attain their greatest volume when they reach the length of one inch the following August. Then as growth slows down, the removal by mortality again surpasses the gain and the volume declines.

The strong influence of the social and economic influence on attempts in the official management of individual populations of soft clams makes it necessary to reexamine the basic principles of management to determine how leniently or rigidly the authorities should enforce the current standard practice. The conventional basis for conservation procedures is strongly influenced by terrestrial stock raising. Observation in this field shows without question that small organisms grow into big ones and increase in either volume or weight approximately as the cube of a linear dimension. Likewise the poultry or cattle raiser expects to carry the majority of his stock to maturity and this is generally the case unless sloppy technic or unpreventable catastrophic epidemics intervene. The shellfish conservationist, under the influence of this kind of thinking, fully expects a bushel of one-inch clams in a flat to increase to nearly eight bushels of two-inch clams with the addition of the extra inch. He thus feels completely justified in rigidly enforcing the two-inch law, and closing the area to prevent breakage of those clams under two inches. In this he fails to take mortality into account.

The previous description clearly indicates that in two cases in which adequate records were kept, the rate of mortality of the soft clam was far in excess of that normally considered when management programs are formulated. It is particularly significant that the clams reached their greatest volume at the average length of one inch and that the interaction of the subsequent deceleration in growth with the mortality brought about a decline in volume. This fact casts serious doubt on the justification for the two-inch law as a means of maintaining a high yield. There are, however, certain practical considerations. One-inch clams are too small to permit efficient harvesting by conventional methods, and would hardly make a useful product for the consumer. In addition the shells are so thin and delicate at that size that losses from breakage might detract from the abundance of the material. Likewise, from the commercial point of view the two-inch clam is about as small as is practicable for ordinary consumption.

It would thus appear that there is no necessity for any relaxation of the law. However, it is possible to consider the management of dense sets as they approach maturity in a different light. Since dense accumulations of clams somewhat over one inch in length do not necessarily forecast a similar dense accumulation of larger ones at a later date, it is sometimes advisable to make such areas available for commercial exploitation as soon as sufficient clams reach a length of two inches to make digging worthwhile. Under conditions similar to those of the two sets just discussed, a reasonable time would be during the summer or fall when the clams are three years old. Under an ideal management system, periodic determinations of the density and length of the clams would make it possible to determine the future trend. As a working rule any marked reductions in numbers per unit area between periods of sampling would indicate a probable diminution in total volume of available clams and would give factual data to aid consultant biologists express an authoritative opinion. As observations of this kind are accumulated, a background of experience can be built up that may make it possible to make reasonable judgments as to the most advantageous program of management for a variety of individual situations.

GROWTH OF MOLLUSCS IN TANKS

BY

HARRY J. TURNER, JR.

Recently there has been considerable interest in the possibility of growing shellfish in excavated salt water ponds on a commercial scale. In Massachusetts this interest has been stimulated by the desire of a number of individuals to establish privately-owned growing grounds in localities where popular opinion resists private ownership or control of traditional public fishing areas. From the biological point of view it has been suggested that it might be possible to control conditions in salt water ponds so as to achieve propagation and growth on the same scale that occurs occassionally under natural conditions. It has been supposed that the prodigious reproductive potential might be utilized efficiently by retaining all the larvae within a pond, thus preventing losses due to dispersal. In addition there is the attractive possibility of stimulating growth by optimal feeding and of maintaining a high survival rate by the exclusion of predators. However, the success of such a venture depends on the determination of the conditions that favor the existance and growth of commercial molluscs and in the maintainance of these conditions at low enough cost to make the marketing of the final product profitable.

At the present stage of the knowledge of the biology of commercial molluscs there are a number of gaps in the essential information that is needed for shellfish farming in salt water ponds. Little is known about the optimal salinity for any species, and still less is known about their food requirements. Spawning has been induced under laboratory conditions, but the factors which influence it in the natural environment are obscure. Under laboratory conditions and by the use of meticulous care the larvae of a number of species have been carried through to metamorphosis in high concentrations but there is no information on how this process might work on a large scale. Finally there is the question as to whether or not it would be possible to maintain a body of impounded water in such a way that it would be equivalent to, or possess the as yet unknown qualities of the waters of an estuary or the ocean.

Previous attempts at setting up experiments in salt water pond culture failed because the chosen sites were so situated with respect to the fresh-water table that it was impossible to maintain the salinity at a reasonable level. It was apparent that a prolonged inquiry into the nature of the fresh water table along the coast and the costly excavations of new ponds would not be justified until preliminary experiments indicated that one or more of the commercial molluscs could survive and grow in impounded salt waters.

To test the latter, experiments on a limited scale were made in a number of outdoor tanks. The experiments were designed to determine what species of commercial molluscs would survive and grow in impounded salt water, the optimal salinity for growth of any species, and the effect of feeding with mass-produced natural food, i.e. phytoplankton. A rectangular concrete tank with a capacity of 4,800 gallons was divided into four compartments of 1,200 gallon capacity each, by wooden partitions. One compartment was supplied with running sea water of salinity 31-32°/oo at a rate of two gallons per minute. The other three were filled with sea water which was allowed to remain stagnant. In one of these the salinity was maintained at full strength (31-32°/oo) and in the other two a calculated amount of fresh water was added to reduce the salinity to lower levels. The wooden partitions separating the compartments were not perfectly tight so that the water in each had a tendency to mix slowly with that of the adjacent compartments. This made is necessary to adjust the salinity at weekly intervals by adding small amounts of fresh or salt water and draining off the excess. The salinities and temperatures were checked daily.

Small quantities of potassium nitrate and sodium phosphate were added to each of the stagnant tanks from time to time to act as a fertilizer to produce rapidly a rich growth of phytoplankton. (Note. In large scale work it is possible to use any of a number of commercial fertilizers that contain the proper ratio of potassium, nitrogen, and phosphorus.) The composition of the phytoplankton, predominantly small green flagellates and *Chlorella,* was essentially constant in the three stagnant tanks, undoubtedly because of the slow intermixing of the waters. Likewise, the temperature was reasonably constant in all tanks varying between 20° and 22° C throughout the period of the experiment.

Soft clams, quahaugs, oysters, mussels, and bay scallops were placed in each tank. Specimens were selected so that the average longest dimension of each lot of each species was approximately one inch to facilitate comparisons with earlier growth experiments of Belding for natural conditions. Twenty-five specimens of each species were placed in each tank. The oysters and bay scallops were placed on the bottom. The mussels were allowed to attach to masonite panels, each one foot square and suspended one foot below the surface. The soft clams and quahaugs were planted in wet sand in wooden buckets 13 inches in diameter and lowered to the bottom of each tank. The experiment was set up in the latter part of June and the following conditions were maintained:

Compartment	Salinity	Feeding	Water
1	31-32°/oo	none	running 2 gals/min
2	31-32°/oo	fertilized	stagnant
3	25-28°/oo	"	"
4	19-21°/oo	"	"

The soft clams, mussels, oysters, and scallops all died in compartments 3 and 4 during the first two weeks of the experiment. The oysters and scallops died in compartment 2 during the third and fourth weeks and the mussels became weakened and dropped off the panel. All species survived in compartment 1. The quahaugs remained alive in all compartments and showed visible signs of growth in compartments 2 and 3. The oysters, scallops and soft clams in compartment 1 showed no signs of growth.

The first four weeks of the experiment indicated that the conditions prevailing in the tanks were suitable for the growth of quahaugs but not of the other species. It was also clear that a salinity range of 19-21°/oo was below the limit at which quahaugs would grow, although it did not kill them. The salinity in compartment 4 was then raised and maintained within a range of 23-25°/oo and the experiment was continued for two additional months. At the end of the three month period the quahaugs were removed and the new shell growth was measured. The following results were obtained:

Compartment	Salinity	Maximal growth	Average growth	Minimal growth
1	31-32°/oo	0	0	0
2	31-32°/oo	10.0 mm	5.5	2.4 all grew
3	25-28°/oo	14.5 mm	8.6	4.0 one died
4*	23-25°/oo	12.5 mm	6.7	2.4 one died
4**	19-21°/oo	0	0	0

* Two months only
** One month only

The growth obtained in compartments 3 and 4 compare favorably with average determinations previously made by Belding for comparable periods under natural conditions around Cape Cod. The relatively poorer growth in the high salinity water of compartment 2 suggests a reason why this species is most abundant in the lower estuaries and bays and is seldom taken in the open ocean. The resumption in growth of the specimens in compartment 4 when the salinity was raised even after a month of inhibition by low salinity shows the remarkable tolerance of this species to incursions of fresh water and ability to survive for long periods under unfavorable conditions.

The failure of the quahaugs to grow in compartment 1 supplied with running water was ascribed to a deficiency of food. The conditions in both compartments were essentially the same but stagnant compartment 2 contained a dense accumulation of green phytoplankton while compartment 1 received only such materials as was present in the natural sea water and there may have been additional demands on this by the surviving soft clams, oysters, scallops and mussels.

It is of particular interest to note that growth of quahaugs took place in the compartments containing stagnant water in the absence of any appreciable current. The early investigators held a unanimous opinion that under natural conditions an appreciable current was necessary to bring in a continuous supply of food and remove waste products. In the compartments, weak convection currents caused by diurnal heating and cooling were just sufficient to maintain the phytoplankton in suspension but no more.

The failure in the survival of the soft clams, oysters, mussels, and bay scallops in all the compartments containing stagnant water is unexplained. They are all known to exist in localities where temperature and salinity levels of those in at least one of the compartments prevail. There is the distinct possibility that these species are unable to feed in waters containing high concentrations of phytoplankton. Loosanoff has shown that oysters are unable to filter when the water contains high concentrations of suspended matter and there are indications that abnormal concentrations of certain phytoplankton are detrimental to oyster populations under natural conditions. The failure of any of these species to grow in the compartment supplied with running water must be taken to indicate that the water supplied was too low in food. The high salinity may have had some inhibitory effect on the oysters and the soft clams which appear to occur frequently in waters of lower salinity but the blue mussel which is often an oceanic species would not have been thus affected.

There is considerable to be learned, not only about the feeding preferences and salinity requirements of these species but also the effect of a constant environment as opposed to a varying one. The conditions within the tanks were rather constant when compared to those of the estuary. There the rise and fall of the tide either alternately exposes and wets the organisms or imposes rythmic variations in hydrostatic pressure. In addition the temperature and salinity may change with each ebb and flood of the tide and variable patterns of the winds and waves may frequently alter the concentration of suspended matter. These conditions require further investigation to determine if they may have any stimulating effect on species which can not be maintained in a constant environment.

The results of the experiments clearly show that quahaugs can be grown satisfactorily in impounded waters where a salinity range of 23-28°/₀₀ is maintained and an abundant phytoplankton growth is stimulated by the addition of fertilizer. The growth, as determined by the experiments is not exceptional but is comparable with that of average conditions in the natural environment. There is one factor that must be considered in designing experiments on a larger scale. The amount of calcium required to build up the shell is vastly greater than is contained in anything but enormous volumes of sea water. The problem did not appear in the experiments just described because the ratio of water volume to the quantity of quahaugs was so great as to prevent any effects of calcium depletion. However, any reasonably shallow pond with the bottom paved with growing quahaugs, would undoubtedly become deficient in calcium.

A REVIEW OF THE BIOLOGY OF SOME COMMERCIAL MOLLUSCS OF THE EAST COAST OF NORTH AMERICA

BY

HARRY J. TURNER, JR.

INTRODUCTION

Within the last ten years more than half a million dollars have been spent on biological investigations of various species of commercially important molluscs in the hope that sufficient information could be accumulated to provide a basis for the development of methods of increasing production. The seemingly diffuse projects of federal, state, and private services have been remarkably well co-ordinated with a minimum of duplication of effort and a maximum of exchange of information. The vast scope of the combined investigations has necessitated recording a large amount of the information in the form of temporary or preliminary reports such as mimeographed circulars, records of conferences, and other similar documents that are not generally available, and a considerable amount of information has been exchanged in personal communications between investigators. In addition, a number of minor aspects of basic problems have been followed only as far as necessary for immediate needs and abandoned before being sufficiently completed to justify formal publication.

The purpose of this review is to summarize, insofar as possible, these significant recent advances in the knowledge of the biology of the commercial molluscs of the East Coast of North America, to relate them to information contained in the older literature, and to point out gaps in our present knowledge which need filling in order to provide a more complete understanding of the problems of increasing the production of shellfish. The biology of the oyster has been adequately reviewed by Korringa (1952) and will be introduced in the following discussion only in cases where it relates to fundamental problems concerned with other species.

In general, a mollusc to be of commercial value must have edible qualities and flavor that appeal to the public; the requisite size that permits economical extraction of the edible portions; and a tendency to form colonies or aggregations so that they may be gathered in quantity. The commercial marine molluscs of the East Coast of North America include less than a dozen of the several hundred species that inhabit that region. The soft clam, hard clam, bay scallop and sea scallop have been of great importance of a long time. The razor clam is marketed in considerable quantity in certain localities. During World War II fisheries for the sea clam, blue mussel, and ocean quahaug were developed, but only the sea clam fishery has remained at a high level since 1946.

There are a few additional molluscs that are marketed in small quantities but their importance in the total economy of the mollusc fisheries is practically insignificant. The small periwinkle, *Littorina,* is esteemed by certain groups of recent European extraction. This little snail, although often so abundant that it may be gathered in quantity, has the disadvantage that the tiny morsels of meat must be manually extracted after steaming. At the other extreme the large conch, *Busycon*, may contain nearly a pound of edible substance, but because it is a carnivorous predator, its abundance is limited, and its wandering habits make it difficult to capture in quantity.

It is of passing interest to note that the contemporary importance of commercial molluscs has a historical background in the food habits of the American aborigines. Numerous shell heaps along the New England coast clearly indicate that the coastal American Indian relied heavily on marine molluscs as a dependable source of food. Likewise the types of shells found in these heaps correspond closely to those of shellfish that now appear in our local fish market. Apparently the Indians preferred species that were reasonably large and locally abundant just as much as does the present-day clam digger or scallop dragger.

The names of the various commercial molluscs that will appear in the following discussion will in general be the common or popular names that are customarily used in commercial publications. The usual names are listed in the following table with other common names and scientific designations:

Common Name	Other Common Names	Scientific Names and Synonyms
Soft Clam	Steamer Clam Long Clam Sedge Clam Mannino	*Mya arenaria*
Hard Clam	Quohog Quahaug Quauhog Little neck (when small) Cherrystone (when small)	*Venus mercenaria* *Mercenaria mercenaria*
Sea Clam	Surf Clam Skimmer Clam Hen Clam Dipper	*Mactra solidissima* *Spissula solidissima*
Razor Clam	Razor Fish	*Ensis directus*
Bay Scallop	Cape Scallop	*Pecten irradians*
Sea Scallop*	Giant Scallop Maine Scallop Digby Scallop	*Pecten grandis* *Pecten magellanicus* *Placopecten magellanicus* *Pecten tenuicostatus*
Blue Mussel	Edible Mussel	*Mytilus edulis*
Ocean Quahaug	Mahogany Quahog Black Quahog Ocean Clam	*Arctica islandica* *Cyprina islandica*
Oyster	Commonly called by point of origin	*Ostrea virginica* *Gryphaea virginica* *Crassostrea virginica*

* The occurrence of sea scallops in the inshore bays of Maine has occasionally caused them to be confused in the literature with the bay scallop of the more southern waters.

SOURCES

Early accounts of investigations of the biology of commercial molluscs are contained in publications of the U. S. Bureau of Fisheries, and reports of the Conservation Departments of Rhode Island and Massachusetts published in the early years of the present century. The principal interest was directed toward problems of propagation and culture of the soft shell clam, *Mya arenaria.* Important contributions by Kellogg (U. S. Bureau of Fisheries) and Mead (State of Rhode Island) provided an understanding of life history of this species and established a general pattern that was applicable to others. Belding (Commonwealth of Massachusetts) carried on a series of continuing investigations of the soft clam, *Mya,* the quahaug, *Venus,* the surf clam, *Mactra,* and the bay scallop, *Pecten* from 1905 to 1911. Accounts of these investigations appear in the Annual Reports of the Commissioners of the Division of Fisheries and Game, Commonwealth of Massachusetts. Important Special Reports were also published. Later Belding published summarized accounts of the soft clam fishery, the quahaug fishery, and the bay scallop fishery of Massachusetts in 1931 as a special Marine Fisheries Series for the Massachusetts Division of Fisheries and Game. Other original contributions include those of Drew on the sea scallop (University of Maine Studies, 1906), Field on the blue mussel (Bull. U. S. Bureau Fish, 1922), Gutsell on the bay scallop (Bull. U. S. Bureau Fish, 1931).

A revival of interest in the commercial molluscs after World War II stimulated a renewal of investigations in a number of centers. These included The Atlantic Biological Station, St. Andrews, New Brunswick (Fisheries Research Board of Canada), Maine Department of Sea and Shore Fisheries, and the Woods Hole Oceanographic Institution (private research institution in Massachusetts). As the interest widened, the Atlantic States Marine Fisheries Commission took over as a coördinating agency and sponsored a special committee of Clam Technicians. Other groups engaged in shellfish research at this time included the Narragansett Marine Laboratory (University of Rhode Island), Rutgers University (New Jersey), The New York Conservation Department, The Virginia Fisheries Laboratory, and the Maryland Department of Research and Education.

A special federal appropriation to the U. S. Fish and Wildlife Service in 1949 created additional facilities for investigations of the soft and hard clams with centers at Boothbay Harbor, Maine, Newburyport, Mass., Kingston, Rhode Island, and Milford, Conn. Coordination of the various research projects was maintained through the Atlantic States Marine Fisheries Commission and the U. S. Fish and Wildlife Service.

Special mention must be made of the valuable contributions on the reproductive physiology of a number of commercial molluscs made by Dr. V. L. Loosanoff and his associates at the U. S. Fish and Wildlife Laboratory at Milford, Conn. Methods have been developed for the conditioning, spawning, and raising the larvae of a number of species at any time of the year. It may be expected that these techniques will make it possible to investigate the most obscure period in the life histories of these species.

The fund of information accumulated by these various groups is available only through a limited number of outlets. The Woods Hole Oceanographic Institution, under contract to the Division of Marine Fisheries, Commonwealth of Massachusetts, has published annual reports through that agency. Special publications have been issued by the Maine Department of Sea and Shore Fisheries from time to time. Contributions of the Milford Laboratory of the U. S. Fish and Wildlife Service have for the most part appeared in scientific journals although a number of Fisheries Leaflets are available in mimeograph form. Chestnut (1951) has summarized the biology and natural history of a number of species and discussed problems associated with the commercial shellfisheries of North Carolina. The most extensive summaries of the works of the combined agencies, which are unfortunately not readily available, are transcriptions of papers and discussions in conferences held in Boothbay Harbor, Maine in 1952 and 1953 sponsored by the U. S. Fish and Wildlife Service and attended by representatives of most of the co-operating agencies. These papers were delivered to a restricted audience as preliminary reports and were not intended for general distribution. However, a considerable amount of the material has been presented at meetings of The National Shellfisheries Association and printed in the Proceedings of that agency. It is the intent of the authors of these papers to consider their material as unpublished until its appearance in a standard periodical. References will be made to both the Conference notes and The Proceedings of the National Shellfisheries Association only where the material has a direct bearing on the subject under discussion and it is to be understood that each author is to retain priority. He may revise, amplify, or delete this preliminary material in the formal publication.

Numerous contributions which relate to fundamental problems of the biology of commercial molluscs have appeared from time to time in scientific journals in Europe. Among important contributors are Thorson of Denmark, Verwey and Maas Geesteranus of the Netherlands, and Cole and Knight-Jones of England. The foregoing is not intended to be a complete survey of contributors and publications in the field, but rather a summary of the more important ones. Numerous additions will be made throughout the text as they apply to the subject under discussion.

THE FUNDAMENTAL PROBLEM

The fundamental problem that besets all the shellfish industries is that molluscs are extremely erratic in their propagation, and variable in their growth and survival. Isolated localities may be phenomenally productive at one time and completely barren for long periods. Individual species vary so greatly in abundance from time to time that shellfishing is considered a precarious occupation with the erratic supply affecting the marketing and associated industries to such an extent that modern methods of food processing and distribution are difficult to apply.

The gaps in our present knowledge of the chain of events that bring about a mature crop of shellfish are so extensive that the actual occurrence of such a crop appears to be accidental. The general developmental pattern common to most species involves spawning, fertilization, a prolonged free-swimming existence, setting, and growth. During this chain of events there are apparently such a large number of interacting physical and biological factors affecting survival that it sometimes seems curious that any of the individuals ever live to maturity. Thus in the last analysis the fundamental problem involves the determination of these factors and their individual relative importance in the hope that certain factors can either be regulated or controlled to expand the actual production toward the theoretical potential.

MORPHOLOGY AND EMBRYOLOGY

Few general texts on invertebrate anatomy contain detailed descriptions of the morphology of commercial molluscs because fresh water pelecypods have been more popular for dissection and study, particularly at the student level. There are, however, a number of works that deal with the morphology of various commercial molluscs in sufficient detail to provide the professional investigator with an adequate knowledge of the anatomy of any particular species.

The soft clam, *Mya arenaria,* has been described in minute detail by Vlés (1909). This little-known work is a 141 page monograph containing numerous original diagrams and plates illustrating the body plan, organ systems, and structures of individual organs. An extensive bibliography of the European literature on the soft clam makes the publication particularly valuable to Canadian and American investigators.

The anatomy of the hard clam, *Venus mercenaria,* is occassionally depicted in general texts. However, the most concise and useful account is that of Belding (1931a). In addition to a verbal description, there is an excellent photograph of a model of a partially dissected hard clam at the Museum of Natural History in New York. All of the essential organs are clearly illustrated in sufficient detail to provide a general understanding of the anatomy of the species

A similar account of the anatomy of the bay scallop, *Pecten irradians,* by Belding (1931b) contains a number of original drawings illustrating the relationships of the gross structures of this species. For greater detail, the work of Gutsell (1930) may be consulted.

The anatomy of the sea scallop, *Pecten grandis,* was carefully described by Drew (1906). A short verbal account by Posgay (1950) is sufficiently detailed to provide a general knowledge of the general morphology of the species.

Field's (1922) exhaustive work on the edible mussel *Mytilus edulis* contains descriptions and illustrations of the various organs of this species. Additional accounts of the physiology and behaviour make this paper extremely valuable.

Fertilization, segmentation of the egg, and early embryology follow a similar plan in all species of commercial molluscs. Descriptions and figures for the soft clam, hard clam, and bay scallop are given in the papers of Belding (1931, 1931a, 1931b). For the sea scallop the work of Drew (1906) may be consulted.

The late embryology including the larval development is of considerable importance in the recognition and identification of the larvae of commercial molluscs. Until recently the work of Stafford (1912) has been considered the standard reference. The illustrations are somewhat diagramatic which detracts from their value as recognition aids. Sullivan (1948) has depicted the larval stages of a number of molluscs with photomicrographs, which are more suited to the needs of the investigator. The chief drawback to both these publications lies in the methods of obtaining the material. Neither Sullivan nor Stafford was able to raise the larvae under laboratory conditions and depended on materials taken in plakton samples. In the course of working backward stage by stage there is a possibility that errors in identification may have been introduced.

The most satisfactory illustrations of the larval stages of the commercial molluscs are unpublished sets of photomicrographs made by Loosanoff. The specimens from which these were taken were spawned, fertilized and raised in the laboratory and there is no question as to their identity. A limited number of these sets have been available at the U. S. Fish and Wildlife Service Laboratory at Milford, Conn. Loosanoff has also prepared and distributed a limited number of microscope-slide preparations of fixed and stained larvae.

DISTRIBUTION

The geographical distribution of commercial molluscs is well documented because of the widespread interest in malacology and the notes of many shell collectors. The range of any species may be readily determined by checking through the "Nautilus" where records of collections have been frequently noted. For ordinary purposes Pratt's "Manual of the Common Invertebrate Animals" (1948) is sufficiently accurate in the ranges given. When absolute accuracy is desired, consideration must be given to the difference between the extreme range of any species and the effective continuous range. Certain species such as the oyster and the hard clam extend continuously northward to approximately the latitude of Cape Cod. Both species occur beyond this limit in isolated local populations which may be relicts of former times when the climate was warmer, or local introductions where special conditions permitted survival and propagation. The accepted ranges are given in the following table.

Name	Continuous Range	Relict or New Isolated Populations	Remarks
Soft Clam	Arctic to Cape Hatteras		Reported occasionally from South Carolina
Hard Clam	Cape Cod to Texas	Salem, Mass. Casco Bay, Maine St. Andrews, N. B. Gulf of St. Lawrence	Setting infrequent beyond continuous range
Sea Clam	Labrador to Cape Hatteras		
Oyster	Cape Cod to Gulf of Mexico	Great Bay, N. H. Sheepscot River, Maine Gulf of St. Lawrence	
Bay Scallop	Cape Cod to Texas	Scituate, Mass. Cohasset, Mass.	
Sea Scallop	Labrador to New Jersey		Reported in deep water as far south as North Carolina
Edible Mussel	Arctic to North Carolina		
Razor Clam	Labrador to Florida		
Ocean Quahaug	Arctic to Long Island		Found only in deep water near southern boundary

The ecological distribution of most species has received relatively little attention. Ecological distribution is used here to mean the inshore-offshore distribution or occurrence in various environmental subdivisions at any given latitude. Belding (1909) has mapped the abundance of the soft clam, the hard clam, and the bay scallop along the coast of Massachusetts. An analysis of these maps indicates that each species exhibits a general preference for some portion of an inshore-offshore habitat starting with the upper estuary and extending to the oceanic waters. More recent observations by others have carried this distributional system to oceanic waters of considerable depth.

Mya, the soft clam, generally inhabits the upper parts of estuaries which suggests a preference for brackish water. However, there are a number of instances in which it occurs at the heads of bays and inlets along the lower estuarine zone where there may be no significant reduction in salinity. Occasional populations have been observed on bars far out in the high salinity waters (Belding, 1953). In general, however, the upper estuary appears to be the preferred habitat.

Venus, the hard clam, occurs most frequently in the lower estuary. It is seldom found in the upper estuary but there are exceptional instances of an oceanic habitat. A large population has existed for a long time along certain shoals in Nantucket Sound, an oceanic environment for all practical purposes. This particular population consists entirely of large specimens blunted with age, all of uniform size. The complete absence of young specimens makes it appear that this population originated as a single year class. In general, productive populations of mixed year classes with continuous recruitment normally occur in the lower estuary.

Pecten irradians, the bay scallop, is found in a variety of localities, most often in the lower estuary and the oceanic zone immediately beyond the mouth of the estuary. It does, however, frequently invade the upper estuary.

Mactra, the sea clam, has been shown by Belding (1909a) and others to be almost exclusively oceanic. Its preferred habitat is the zone of surf-washed sands from the low tide mark to depths of several fathoms. The texture of the substratum and the high oxygen content of the surf zone appear to influence this zonation. Sea clams have never been recorded from muddy sands.

Arctica, the ocean quahaug, has been taken from the deep mud-sand zone exclusively (DeWolfe and Loosanoff, 1945). Surveys conducted by the author (Turner, 1949) indicate that temperature may be one of the factors influencing this zonation. South of Cape Cod it is never found in depths less than 80 feet and north of Cape Cod, where the water is cooler, it has been taken at 60 feet. Difficulties that have been encountered in keeping this species alive long enough to market it during the summer months demonstrate that its thermal death point is low, probably about 55-60°F. This may be the factor that prevents its existence in the shallow water where the temperature rises above that point. The preference for muddy sand is unexplained and may not always occur. Recent underwater photographs taken by Posgay have shown siphons of large molluscs in rippled sand on Georges Bank in depths greater than 200 feet. Shells of dead specimens in the same photographs have been definitely identified as those of the ocean quahaug.

Pecten grandis, the sea scallop, is clearly a deep water oceanic species at the latitude of Massachusetts. Posgay (1950) and Dickey (1953) have independently determined that the thermal death point of this species ranges between 21 and 23°C. It is thus apparent that high temperatures limit its distribution to the cold offshore waters from Massachusetts south. In Maine, where the summer temperature of inshore waters is lower, the sea scallop occurs in deep bays between headlands.

The causal factors influencing the north-south range, and the inshore-offshore distribution of commercial molluscs require further study. There appears to be definite need for investigations of the exact ecological requirements of most species. The north and south boundaries of the range of each species may be determined by temperature barriers and the concepts of Hutchins (1947) might profitably be employed to explain their locations. The inshore-offshore zonation may be influenced by salinity, temperature, and other unknown factors. It would be profitable to investigate the influence of temperature and salinity on spawning, larval survival, and rates of growth. In addition the presence or absence of food, predators, competitors, and areas suitable for the existance of each species in all the various zones should be determined.

SPAWNING

Spawning has been induced in practically all the East Coast estuarine molluscs by Loosanoff (U. S. Fish and Wildlife Service Laboratory, Milford, Conn.). His technic involves a manipulation of the temperature of the water in the laboratory to favor maturation of the gametes and a final temperature shock to trigger the spawning (Loosanoff and Davis, 1950). However, under natural conditions the factors that induce spawning are still obscure. Korringa (1947) has related the spawning of the European oyster to phases of the moon and has interpreted the immediate stimulus to be changes in the tidal amplitude. He also cited evidence that this factor may influence the spawning of the soft clam. However, Loosanoff and Nomejeko (1951) in a series of observations on the spawning of the American East Coast oyster could find no correlation between spawning and the lunar phases.

The factors that induce spawning are undoubtedly numerous and complex, but the bulk of evidence at the present time suggests that temperature is of greatest importance. The spawning season of most species has been determined by a number of investigators to occur some time between the late spring and the end of the summer while the temperature is rising. In fact, Loosanoff's techniques involve reproducing these conditions in the laboratory on an accelerated scale. Loosanoff and Davis (1951) have further shown the importance of temperature by demonstrating experimentally that low temperatures will inhibit spawning in the oyster and the hard clam. The one exception is the sea scallop which spawns in the fall (Posgay 1953) and appears to be triggered by a drop rather than a rise in temperature.

It is reasonable to suppose that spawning must occur simultaniously among a mass of individuals to insure the presence of spermatozoa in the water at the same time that the eggs are present. The investigations of Galtsoff (1930), Nelson (1940), and Young (1946) indicate that the reproductive products of one sex may influence the spawning reactions of the other so that a chain reaction may be set off in any one population.

From the practical point of view it would be desirable to determine the maximal separation at which a pair of molluscs can effectively propagate. The matter becomes of considerable importance when the effect of exploitation is considered. Exploitation tends to thin out the population and increase the distance between individuals. It is conceivable that separation might become so great that the spawned products of one individual would be too dilute to stimulate the reaction in another of the opposite sex, or if numbers of individuals spawned simultaneously in response to some other stimulus, they might be so far apart that inadequate fertilization would take place. At the present time there is no information on the viability of the gametes or the necessary ratio of spermatozoa to eggs.

Various estimates have been made by one means or another of the numbers of eggs annually produced by the commercial molluscs and the estimates for any one species vary considerably. However, it may be safely assumed from the estimates of most competent observers that all commercial molluscs produce one or more million eggs per female annually. Stickney (1953) has attempted to determine whether the number of eggs present in the soft clam might vary from year to year and thus influence the reproductive potential. Some evidence of variation was found, but his investigations were terminated before conclusive results were attained.

THE LARVAL PERIOD

The free-swimming larval period of commercial molluscs is presumed to be precarious, but extensive knowledge of what actually happens at this time is almost completely lacking. Kellogg (1901), Mead (1900-1904), and Belding (1931) established the fact that the fertilized eggs of most species become motile within the first 24-48 hours and Loosanoff has observed subsequent stages of larvae of a number of species. The general belief held for over half a century is that the free-swimming larvae drift helplessly in the water for a period of days or weeks; their swiming powers being just sufficient to overcome their sinking rate and thus providing only the effect of neutral buoyancy. During this period these larvae are believed to be exposed to the predations of numerous unspecified predators, affected favorably or adversely by unspecified physical conditions, with the few survivors finally sinking to the bottom to metamorphose and attach if the substratum happens to be suitable.

Loosanoff has confirmed previous determinations of the duration of the larval period by rearing the larvae fed on various species of small phytoplankton in the laboratory. The swimming ability, however, has not been investigated. The swimming ability becomes considerably important in light of new methods developed by Ketchum for the estimation of the flushing rate of estuaries. Ketchum (1951) has evolved a method for determining how long it takes a particle of water to traverse the distance from the head of an estuary to the mouth, if certain bathymetric and tidal data are known. If mollusc larvae are for all practical purposes neutrally buoyant, they would behave essentially like particles of water and calculations of the percentage loss by tidal flushing could be easily made. On the other hand, if the swimming behaviour of the larvae influences their distribution in any way that would make them behave differently from mere particles of water, Ketchum's formulae would not apply. The apparent preference of different species for different zones, discussed in a previous section, makes it seem likely that their larvae have individual properties which influence their arrival at the preferred zones at the time of metamorphosis.

Loosanoff, Miller and Smith (1951) have experimentally determined the effect of temperature on the duration of the larval period of the hard clam and have opened up interesting possibilities of determining the probability of the survival or retention of larvae within an estuary. At the optimal temperature, the larvae of the hard clam begin to set in as little as seven days after fertilization while unfavorable temperatures may extend the period to as much as 30 days. It is reasonable to suppose that fewer larvae will be removed from an estuary by tidal flushing when the larval period is short than when it is long. Thus the probability of a successful set may be increased when spawning coincides with the beginning of a period of optimal temperature conditions. If temperature should influence in a similar way the larval period of other species, both estuarine and oceanic, there is an additional possibility that a shortened larval period may decrease larval mortality from predation and thus favor high percentages of survival to the setting stage.

The behavior and properties of the larvae may have something to do with the origin of aggregations of the adults. It is a common observation that all commercial molluscs often occur in discrete colonies, of which all the members may be of the same year class (Turner, 1952). Kellogg (1903) suggested that the formation of such colonies resulted from the concentrating action of water motion, functioning in much the same way that the rotation of tea in a cup will concentrate the tea leaves in the center. Belding (1909) amplified this view basing the hypothesis on the eddy conditions prevailing around the Rowley Reef, Plum Island Sound, which obtained a set of soft clams in 1906.

There is a definite need for knowledge of larval behaviour and physiology of all species of commercial molluscs. It would be desirable to know their swimming velocities and sinking rates at all stages of development, their reactions to fields of force such as gravity, light intensity, temperature gradients, salinity gradients, oxygen, degrees of turbulence, and to differences in density of the water and hydrostatic pressure. This information would make it possible to determine the probable directions that a larva would take during its period of development under a given set of circumstances. With this knowledge it might be possible to maintain spawning stocks in advantageous localities and to establish new ones where they would be most effective.

METAMORPHOSIS AND SETTING

Metamorphosis is the transition of the free living to the sedentary stage. The most important change in a practical sense is the loss of the swimming organs and the development of the byssus. The byssus is a thread elaborated by a special organ which makes it possible for the organism to attach itself to some solid object. It persists throughout life in the mussel and for a considerable time in the bay scallop. Ryder (1889) first described it in the young soft clam, and others have demonstrated its existence in various species. The physiology of metamorphosis and setting of most species is poorly understood. Loosanoff et al. (1951) have demonstrated that the larval age at metamorphosis may vary within a group produced by the spawning of a single pair of hard clams and that the swimming organ degenerates gradually as the muscular foot develops. Loosanoff defines the setting stage as the time the byssal gland appears. A more detailed description has been given by Carriker (1951 a).

There has been considerable speculation as to whether or not larvae exhibit a positive selection of the substratum. The early workers considered that setting was more or less a matter of chance with those individuals "falling on good ground" surviving. Thorson (1946) reviewed the matter and came to the conclusion that metamorphosis may be a somewhat protracted transitional phase during which a larva may be carried along the bottom by currents so that it may attach whenever it arrives at a suitable substratum. Carriker's (1951a) observations on the setting of the hard clam, which are in agreement with those of Loosanoff, indicate that metamorphosing larvae of this species could undoubtedly be carried considerable distances over the bottom by currents and in addition show definite preferences for a certain type of substratum. According to Carriker's observations, the transitional phase during which both the foot and the swimming organ are present is one of considerable activity in both swimming and crawling, as if the organism were testing various kinds of substrata. Temporary attachment takes place with the disappearance of the swimming organ but active crawling continues. The first attachment that is more or less permanent occurs when the organism finds a solid surface covered with a thin layer of silt. The byssus is fastened to the solid surface with the tiny clam suspended in the silt above. Later when the byssus degenerates the organism works its way down between the sand grains of the substratum.

In most other cases there is some question as to what constitutes a suitable substratum. The author has found soft clams in almost every conceivable kind of sediment ranging from soft yielding mud to coarse stony gravel and also clean washed sand or black odorous peat. It is clear that these qualities influence growth and shape (Swan 1952, Pratt 1953) but the fact that the adults occur in them at all indicated some degree of suitability. The sea clam, on the other hand, always requires clean surf-washed sand. The preference of the ocean quahaug has been considered to be muddy sand but, as has already been mentioned, there is some possibility that other substrata may be suitable if certain conditions are favorable.

It is clear the species like the oyster which attach permanently require solid surfaces but it is controversial as to what kinds of surfaces are suitable. Oyster growers have always used clean shell to catch the spat because they have believed that slimed surfaces inhibit setting. However, Cole and Knight-Jones (1949) have determined that slimed surfaces are more suitable than perfectly clean ones provided that silting does not occur.

There is some indication that the bay scallop is favored by eel grass to which the young can attach. Gutsell (1930) has shown that the presence or absence of eel grass in the North Carolina Sounds has affected the setting of bay scallops. Similarly Baird (1953) has found tiny sea scallops attached to strands of erect bryozoa. Fishermen have told the author that they believe the "beard" (tufts of bryozoa) on the sea scallop to be the attachment point of the young because they have found them there. If this is the case, it points to a possible interdependence of species; the scallop forming the substratum for the bryozoan which in turn may form an attachment point for the young scallop. If such an interdependence were to be demonstrated, it might be possible to show how over-exploitation could affect the future of the resources by breaking the chain of events and destroying the physical environment required for repopulation.

Part of the difficulty in investigating the setting behaviour of commercial molluscs, particularly the sand dwelling forms, arises from the fact that setting is seldom observed directly. Setting in sufficient numbers to make observations practicable occurs so sporadically in both time and locality that it generally comes to the attention of the investigator only after the organisms have become established and have grown large enough to be clearly visible. The technics developed by Loosanoff have opened up the possibility of investigating setting behaviour on a laboratory scale. It should be possible to determine if there is any important selectivity for types of substrata in the different species.

EARLY SESSILE EXISTENCE

According to the classical description, burrowing species of commercial mollusc begin their sessile existence at metamorphosis when they reach the substratum and attach their byssus to sand grains. There is no doubt that the oyster selects its permanent and final habitat at metamorphosis because it soon cements itself to a solid surface and loses all organs of locomotion. On the other hand, there is considerable doubt as to the permanence of the first site selected by the burrowing species. Belding (1931) suggested that young soft clams, while still small, may wander about, but he found no evidence that such migrations took place to any significant extent. However, Smith (1952) observed numerous small soft clams attached to the upper surfaces of plastic screens that were set out in the late winter long after there was any possibility of actual setting. Continued investigations showed that the number of young clams in any small area under observation varied from day to day, indicating a considerable amount of moving about. The observations of Smith explained the results of the author (Turner 1948) who had previously achieved some success in supposedly inducing setting by placing sods and thatch on the flats. The sods clearly did not induce setting but rather acted as barriers and accumulation areas for small clams that were either wandering about or being carried by water currents.

Recent observations by the author on the Raccoon Island set in Boston Harbor (Turner, 1953) have demonstrated that entire populations of soft clams may be shifted during their early sessile existence. The sequence of events observed in this instance has led to a concept of "hydrographic concentration" (Turner, 1953). In brief, the hypothesis suggests that the distribution of commercial shellfish may be influenced by the same hydrographic features that affect the zonation and sorting of the particles of the substratum. In any locality where a variety of types of bottom are present, it is assumed that each type of sediment is concentrated in its characteristic position as a result of hydrographic features including currents, waves, and turbulent conditions as they act on particles of different sizes and weights. A typical example is the Raccoon Island area (Quincy, Mass.). Here a steep gravel beach results from a difference in the onshore force of waves which are strong enough to transport pebbles up the beach and the offshore force of the backwash which it too weak to remove them. The stones and pebbles are concentrated on the slope by the interaction of these forces. Likewise the hard flat sandbar extending seaward from the beach at the low tide mark has been deposited by the backwash, which is strong enough to transport sand grains but not pebbles from the beach. Further seaward the sand flat grades to a fine mud extension, where the force of the backwash becomes sufficiently attenuated to permit the lighter particles to settle out. In this way the various sizes of sediments become concetrated in characteristic zones.

The preliminary evidence suggests that developing molluscs are affected in the same manner. When very small, they have properites essentially similar to those of mud particles and thus become concentrated in the appropriate mud-sand zone. As they grow larger their properties change and they react to hydro graphic forces first is if they were sand grains and then as if they were small pebbles

It is evident that some such mechanism as that just described actually took place in the Raccoon Island set of soft clams (Turner, 1953). Other evidence derived from maps of local concentrations of hard clams in Maine published by Dow and Wallace (1951), indicates that some such concentrating mechanism undoubtedly influences the distribution of this species. Recently Verwey (1952) and Maas Geesteranus (1942) have demonstrated that a similar mechanism applies to the edible mussel. In setting, the mussel attaches and remains on erect growths especially algae for some time but later loosens its hold and is carried by water currents. Those that are carried over existing mussel beds attach and remain there permanently. Neither Verwey nor Maas Geesteranus attribute the selection of existing mussel beds as an indication of a directed gregarious tendency, but rather due to transportation by hydrographic forces to suitable localities. In addition, commercial fishermen have reported that the sea clam and sea scallop, both oceanic species, are generally found in restricted local assemblages of high concentration. The fishermen are not clear as to how these assemblages are distributed with respect to the physiography of the bottom but the frequent use of fathometers and other aids indicates that there is some definite relationship and the fishermen seem to have a subconscious knack in locating the beds.

The active motility of the sea scallop and the young sea clam permits them to get off the bottom at frequent intervals, although they appear to swim in random directions. There is, however, a possibility that even these random movements may be directed by water currents to transport the organisms to locations where the strength of the currents diminish.

The entire subject of the formation of assemblages or populatons of commercial molluscs needs thorough study. The biological implications are far reaching in regard to the preservation of the species. It is evident that the general pattern of diffusion and dispersal in most marine environments would scatter larvae far and wide if they are no more than neutrally buoyant. This would ultimately result in such a wide dispersal of individuals as to materially reduce the chances of fertilization of the eggs at spawning and the species would become extinct. The fact that this situation does not occur suggests that a concentrating mechanism of some sort exists.

GROWTH

Probably all organisms have characteristic growth rates determined by the fundamental biological properties of each individual species. These properties establish the maximal rates at which each species can possibly grow under the most favorable conditions, and the maximal size that can be achieved. In addition there may be racial differences within any species. The optimal growth rate is subject to modification under any conditions that may be less than ideal. It is reduced by conditions that reduce the organism's food intake or by those that adversely affect the organism's ability to use the food.

The rate of growth is an exceedingly important factor in the maintenance of stocks of commercial molluscs, not only because it determines how fast exploited populations will be replaced but also because the ratio of growth to mortality determines whether a population is gaining or losing in volume of commercial productivity. In the precarious marine environment, organisms are constantly crowding each other, being eaten, or dying from unknown causes so that fast-growing organisms may be expected to have a better chance of reaching commercial size than those that grow slowly. Factors influencing the growth of commercial molluscs have been studied intensively but only moderate success has been attained in the establishment of an understanding of their relationships.

FUNDAMENTAL GROWTH RATES: Considerable difficulty has been encountered in determining fundamental growth rates for most species of commercial molluscs because the rates are affected by a number of factors encountered in field investigations. Because of this the detection of races has been relatively unsuccessful. Spear (1953) has attempted to determine whether or not the soft clams found along the coast of Maine could be separated into definite races, each with a characteristic growth rate. Reciprocal transplants were made between two adjacent localities, one where the clams grew fast and the other where they grew slowly. Additional transplants were made from other localities to each of these test areas. The results of these experiments showed that the clams grew at a rate characteristic of the locality to which they were transplanted with little detectable influence of original stocks. At an earlier date Newcombe and Kessler (1936) made exhaustive analyses of growth indices of soft clams from various localities, and found significant differences. Spear's experiments now demonstrate that these apparent racial differences were undoubtedly caused by the environmental influence.

FOOD AND GROWTH: The exact nature of the food of commercial molluscs is poorly understood. It has been generally thought to consist of phytoplankton or minute particles of organic detritus. Kellogg (1903), Mead (1901-04) and Belding (1931) observed that most commercial species were favored by rapid movements of the overlying water and concluded independently that strong currents supplied more food and oxygen and removed waste materials more efficiently than slow currents and stagnating conditions. Meade also observed that the soft clam grew at a reduced rate when crowded excessively and suggested that the crowded clams would reduce the food supply in the overlying water faster than it could be renewed.

Careful studies of the availability and kinds of food materials have been made by Coe (1948) who came to the conclusion that certain West Coast molluscs subsist on minute cells and particles of organic detritus. Coe was able to show that such materials prevailed in sufficient abundance to account for the growth of the molluscs, and variations in availability were reflected in changes in the growth rate.

Recently Haskin (1949 and 1952) has demonstrated that the amount of food of an unspecified nature determines the rate of growth and the maximal attainable size of the hard clam. Good agreement was found between the rate of growth and the amount of material available as indicated by the total phosphate and chlorophyl content of the overlying waters. In addition, the meat content of large hard clams degenerated when specimens were transplanted to a locality where the maximal size attainable was smaller. This is a clear indication of the importance of food in the growth of this species. It is evident that food in the poor growing areas was not supplied at a rate sufficient to support the metabolic activities of masses of living material above a critical size and the large transplanted clams had to utilize their own body substances in the same way that any animal does under conditions of starvation. Haskin also determined that the areas of poor growth usually contained large native populations and concluded that hard clams may become so numerous in semi-enclosed bodies of water that they reduce the food supply to a level that is insufficient to support optimal growth

Loosanoff and Engle (1947) have demonstrated with ingenious laboratory experiments that excessive densities of suspended matter inhibit the feeding of the oyster whether the suspended matter consists of suitable food or inert material. This appears to be the possible cause for the decline in the production of oysters in Great South Bay, L. I. where hydrographic changes and agricultural advancements have favored the growth of abnormal blooms of *Chlorella* and other small phytoplankton.

Recent experiments by the author have shown that the hard clam differs from the oyster in that it can utilize *Chlorella* and green flagelates even in concentrations so dense that the water is soupy green. Growths comparable with good average figures observed in the field have been obtained in tanks of stagnant water while specimens in control tanks supplied with running water that was not enriched scarcely grew at all.

Experiments of Posgay (1953) on the sea scallop suggest that this species may utilize a different variety of food from that of the hard clam. Posgay has successfully maintained small sea scallops in indoor tanks supplied with running water cooled to the optimal temperature for the species (6°-10°C) and has observed growth approximating that estimated for the natural environment without adding food.

The kinds of food required by each species of commercial mollusc, and the influence of the various kinds and concentrations need considerably more study, since growth ultimately depends on the amount of food ingested and assimilated.

TEMPERATURE AND GROWTH: All species of commercial molluscs have characteristic north-south distributions with limits of their ranges ultimately determined by critical temperatures. Within each range, however, the exact effect of temperature on growth has received little attention. It is generally supposed that most species of commercial molluscs grow slower at the northern or cold boundaries of the range but little attention has been paid to the warm extreme. Average growth curves for the soft clam have been summarized from the published literature by the author (Turner, 1948) which show progressively slower growth as one passes northward. There is no information on the growth of the soft clam toward the southern extremity of its range (Cape Hatteras) although a number of specimens secured by the author from the Chesapeake Bay have an appearance suggesting that they grow even more rapidly at that latitude. This conflicts with the views of Barnes (1948) who attributed the decline of soft clams in Massachusetts to be caused in part by high temperatures.

Belding has collected specimens of hard clams from the relict population in the Gulf of St. Lawrence with prominent annuli showing that these clams grow less than half as fast as the same species on Cape Cod which is the approximate northern limit of the continuous range of the species. The Gulf of St. Lawrence is apparently endowed with physical features that permit the water to warm up sufficiently to induce spawning in the summer but the annual growing seasons are relatively short.

The experiments and observations of Posgay (1953) on the sea scallop have shown that young specimens grow best at 10°C or lower and that the rate declines as the temperature is raised, death taking place in the neighborhood of 22°C. This thermal death point has been confirmed independently by Dickie (1953). Posgay's experiments have given some indication that young scallops are more tolerant to high temperatures than old ones, which seems to explain reported mortalities in large scallops along the coast in summer. Posgay and the author have determined that the ocean quahaug is susceptible to approximately the same temperature, a matter which has hindered commercial exploitation of this abundant species.

The influence of temperature on growth could be profitably investigated further for all commercial molluscs. In the final analysis, temperature controls the rate at which the fundamental living processes proceed and thus influences the rapidity of feeding, assimilation, and storage of food. Each species appears to have a characteristic upper and lower limit within which these living processes may go on. It is also possible that any one species may contain physiological races with separate temperature limits for each race. Knowledge of this subject might profitably be applied in a practical way if it could be shown that trends in climatic changes were causing shifts in populations. For example, a physiological race adapted to a warm climate might be transplanted to a new latitude, if its counterpart in that latitude had been eliminated by warming.

SALINITY AND GROWTH: The effect of the concentration of sea salts on the growth of commercial molluscs has been for the most part completely neglected. A perusal of over 250 pages of notes containing the minutes of two joint meetings of shellfish investigators fails to reveal any mention of the subject. The effect of salt concentrations on individual functions and the reactions of isolated tissues of molluscs has been investigated at considerable length but has not been related to the growth of the whole animal. An extensive bibliography has been compiled by Pilgrim (1953). It is reasonable to suppose that salinity may have an important bearing on the well-being of various commercial molluscs because many of them inhabit estuaries, where the full salinity of the ocean is modified to some degree by admixtures of fresh water from the land. The apparent preferences of different species for different zones within or near the estuarine environment suggest that each species may be favored by some particular salt concentration. If this should be the case, it is to be expected that deviations from the optimal salinity may have an adverse effect on growth. All commercial molluscs are equipped with some sort of kidney, thus making it likely that each is capable of some degree of osmoregulation. Anderson and Prosser (1953) have recently found confirming indications of this in the hard clam. The concentration of salts in the blood of specimens taken from brackish water has been consistantly higher than that of the surrounding medium. Thus it appears that salt concentrations above or below the optimal level may cause the organisms to expend energy in maintaining their water balance that may otherwise be expended on processes involved with growth. In addition, changes in the salinity of the medium beyond the characteristic tolerance of a species may interfere with a number of fundamental processes. This condition may cause the organism to close its shell and thus be unable to feed, or it may interfere with a number of physiological mechanisms by disturbing the salt balance of the body fluids.

Pilgrim's (1953) investigations of the response of isolated tissues of the edible mussel and the European oyster have demonstrated that such tissues appear to tolerate far wider ranges of salinity than normally occur in the natural environment and the conclusion is drawn that salinity has little influence on the ecological distribution of these species. However, no mention is made as to how it might affect growth. The definite changes that are noted as the salinity is deviated from the optimal, indicate that the well-being of the animal will be similarly affected so that the total response may ultimately influence the rate of growth.

Recent experiments by the author have indicated that growth of the hard clam is favored by a slight dilution of ocean waters to a salinity of 24-28°/oo. This may explain in part the apparent preference of this species for the lower estuary.

There is a definite need for a complete investigation of the effect of the salt concentration on the growth of all commercial molluscs. Such knowledge may be profitably applied to efforts at rehabilitating the various shellfish resources in places where the inroads of human populations have brought about alterations in hydrographic features that may have caused major changes in salinity.

OXYGEN AND GROWTH: The benthic environment with its accumulation of organic material in the substratum may bring about a reduction in the oxygen tension in the layers of water immediately above the bottom. These layers of water are the only ones within reach of a number of bottom-dwelling organisms including many of the commercial molluscs. There appears to be little known about the oxygen requirements of most species. Van Dam (1934) has determined that the soft clam can live for some time without respiring and can make up for the oxygen debt by utilizing an extra amount when oxygen-rich water becomes available. The ability of many species to exist in bottoms with a high organic content makes it seeem likely that they are capable of maintaining themselves on a low oxygen concentration. Similarly the limited distribution of the sea clam in the surf-washed sands, and the poor survival in tanks (author's experience) indicates that this species may require a high concentration of oxygen.

The influence of the concentration of oxygen could be profitably investigated, particularly in view of the increased load of organic materials which the encroachment of human communities has inflicted on semi-enclosed bodies of water.

THE INFLUENCE OF THE SUBSTRATUM ON GROWTH: The early investigators, Kellogg (1903), Meade (1900-1904) and Belding (1931) considered the substratum to be an inert medium that merely supported the sand-dwelling commercial molluscs. However, Belding demonstrated that a substratum was necessary for optimal growth of soft clams, although some growth was obtained in clams placed in submerged boxes with no sand. Belding also suggested that various conditions in the substratum might inhibit shell formation and reduce the growth rate.

Clam diggers have universally observed that the soft clam seems to grow fast and to lay down a thin shell in clean sandy soils while in muddy or gravelly soils the growth is slow and the shell is thick. Swan (1952) confirmed these observations by making reciprocal transfers of boxes of mud and sand and compared the growth and shell characteristics of clams in the boxes with those of the different surroundings. He determined that the growth and shell characteristics were influenced by the substratum rather that the locality. Pratt(1953) conducted similar experiments with the hard clam and found that sand favored faster growth than mud when other factors were eliminated.

It is not clear how the substratum influences the growth of burrowing molluscs. The shells form an effective barrier over most of the body surface but the fringe of the mantle generally overlaps the margins to secrete the periostracum. The naked mantle fringe is thus exposed to the substratum in such a way that the biological processes may be influenced by the constituents of the soil.

Investigations of the influence of the substratum on the growth of commercial molluscs have been hampered by a lack of knowledge of what the important constituents of the substratum really are. Geologists have analyzed soils as to their mineral composition, particle size and assortment, compaction, water content and organic content. There is, however, a definite need for correlations of these and other discoverable factors with the ecology of sand dwelling organisms.

THE EFFECT OF THE TIDE LINE ON GROWTH: Habitats of commercial molluscs vary with the species in respect to the tide line. Verril (1873) recorded soft clams from the half-tide mark to depths as great as 40 fathoms. In general, however, the soft clam is seldom taken far beyond the low tide mark, although south of Cape Cod where the tidal amplitude is relatively small it may be commercially exploited in depths as great as six feet at low tide. It is highly probable that the soft clam does not exist much beyond this depth because hard clam dredgers seldom find it in their catch. It is generally agreed that the soft clam grows slower between the tide lines as the upper limits are approached and it is generally concluded that this is a function of the feeding time.

The hard clam is generally taken at or near the low tide mark to depths of s veral fathoms where exceedingly long-handled implements or power dredges are required. There is little in the way of published material on the effect of depth on growth of this species. The author has observed small, very old specimens in pools on the high marsh where the water is changed only once each tide, but this is an exceptional case. It may be surmised that the food supply in these pools may have been depleted during low tide intervals but other factors such as the character of the substratum, availability of oxygen, and abnormal temperatures may have been responsible for the slow growth.

Growth of the blue mussel which inhabits solid structures between the tide lines has been investigated by Loosanoff and Engle (1943). They have shown that this species grows best at the mean low water level. Growth is slower both below and above this point. The reduction in the growth rate above the low tide level can easily be explained as a result of the limited time of feeding, but the adverse effect of continuous submergence is not explainable.

All the remaining species of commercial molluscs occur below the mean low water mark and there is no information in the literature on the effect of depth on growth except as it may influence temperature.

FACTORS INFLUENCING NATURAL MORTALITY

The sedentary nature of most commercial molluscs limits their ability to react to environmental changes once they have become established. However, all species except the oyster retain some powers of locomotion which enable them to react to their environment to some degree. This ability is in general so restricted that a number of disrupting events in the life of any species can be fatal.

DISRUPTION FROM THE SUBSTRATUM: All species except oysters have some ability to re-establish themselves if disrupted from the substratum. Time-lapse motion pictures taken at the Woods Hole Oceanographic Institution have shown that soft clams up to an inch in length can bury themselves in less than fifteen minutes. This has pictorially confirmed the observations of the early investigators who used this ability of the soft clam in their attempts at reseeding barren areas. All workers are in agreement that this ability declines with increasing size. However, older specimens are generally situated at such great depths in the substratum that disruption rarely occurs.

The hard clam appears to maintain some powers of burrowing throughout its life. The author has even observed very large specimens, blunted with age, re-establish themselves in a matter of hours and it is well known that hard clams in the "little neck" size range can dig in in a matter of minutes.

The razor clam *Ensis* is well known for its ability to burrow rapidly. Once the burrow is made, a specimen can retreat downward to a considerable depth in a few seconds.

The sea clam which lives in the unstable environment near the surf zone has a powerful foot with which it can dig in, jump, and even swim. This gives it an unusual ability to combat the forces of its normal unstable environment. There is a common belief among commercial fishermen that the sea clam tends to congregate when the beds are thinned out by fishing. The absence of true directed movements of the activities of this species makes the belief unlikely. There is, however, a possibility that currents and tides may combine to give definite direction to otherwise random movements.

The blue mussel which is normally attached to some solid structure by means of byssus threads is capable of cutting loose and re-establishing itself in a new locality (Verwey, 1952 and Maas Geesteranus, 1942). Field (1922) has given an account of a mussel moving over the surface of a glass panel by attaching new threads and breaking off the old ones. The author has observed small bay scallops climb up the vertical surface of a glass aquarium in this manner. It is thus apparent that these species have some powers of re-establishing themselves on suitable substratum.

There can be little doubt that it is a serious matter for commercial molluscs to be disrupted from their substratum. The period of highest risk is probably during the winter when storms are most severe and the organisms are inactivated by the cold. Soft clams, hard clams, bay scallops, sea clams, and even ocean quahaugs have been recorded at high levels of the beach after winter storms.

BURIAL AND SMOTHERING: The problem of survival in a substratum that is constantly building up by sedimentation or traveling by dune-like movements is probably quite serious for all inactive commercial molluscs. Slow changes in the contours of various substrata over long periods of time have not been described but casual observations give the impression that such slow changes do occur, with some parts of flats and beaches building up while other parts are eroded away. The question of burial and smothering must be considered in light of these natural processes and also as influenced by commercial digging.

There does not appear to be any published information on the effect of sedimentation on survival of any species except the oyster which will sometimes grow in an elongated form to keep its beak above the mud level and die if the rate of sedimentation is too great. The author has observed numerous "grave-yards" that contain paired shells of soft clams, razor clams and hard clams situated upright in place just as they died, exposed by shifting of channels. The mixture of species suggests some kind of catastrophe of a physical nature rather than a biological one (disease) which would probably be selective for a given species. It seems probable that the original populations were overcome by sedimentation some time in the past.

In studies on effect of digging, Medcof (1948) has observed that small soft clams can dig out to the surface if buried by the excavations of commercial diggers. After reaching the surface the clams then re-establish themselves in an upright position in the soil. Extensive experiments conducted by Glude (1953) have shown that soft clams have a poorer chance of surviving the deeper they are buried. In general, the larger clams survived better than the smaller ones but at a depth of 9 inches the survival of all sizes used in the experiment was extremely low.

PARASITES AND DISEASES: Kellogg (1903) and Mead (1900-04) both described mass mortalities in populations of soft clams and numerous commercial fishermen have reported similar occurrences. The author (Turner, 1948) has characterized these occurrences as "epidemic mortality" but no one has been able to determine the cause. Whenever cases are discovered the clinical picture is pretty much the same. The clams are upright in their burrows, the necks extended, and the viscera completely liquified. Numerous unsuccessful attempts have been made to find soft clams in a sick condition, but the living clams always have appeared healthy and the dead ones so completely decomposed that diagnosis has been out of the question.

Exhaustive investigations of possible parasites of the soft clam have been carried out by Uzmann and Stickney of the U. S. Fish and Wildlife Service. Numbers of species have been listed from the Protozoa, Turbellaria and larval trematodes. In general no connection has been established between these parasites and any serious epidemics in the soft clam.

A condition which limits the shucked yield of the soft clam has been observed by a number of workers and described by the author as "waterbelly", a term commonly used by the fishermen. In the waterbelly clam the reproductive tissue degenerates and the visceral mass becomes filled with a clear amber fluid which is expelled when the body wall is punctured. There are no published studies on the causes of this condition. The author, however, holds the belief that it frequently occurs in large, old specimens and may be an indication of senescence.

Another condition described by the author (Turner, 1953a) as the "tipover" effect may justifiably be discussed in this section. Soft clams, usually small ones, sometimes push themselves out of the substratum, "tip over" and die. The author has suggested that the reaction may be stimulated by the formation of an irritating or poisonous substances in the substratum, but most investigators feel that soft clams react in this manner to any unfavorable influences in the environment. It has also been suggested that irritation from parasites or disease organisms may be involved.

PREDATORS: The commercial molluscs represent the marine counterpart of the terrestrial herbivors and are thus the main source of food for a variety of carnivorous animals. The sedentary nature of most species of commercial molluscs leaves them totally defenseless against the attack of predators and forces them to depend on a high reproductive potential for the maintenance of the species. It has been clearly established within the last ten years for a number of commercial molluscs that the competition between predators and man is so strong that at times the predators have much the better of the situation. The problem has become so serious in the case of the soft clam that a considerable portion of the investigations has been diverted from studies of the biology of the clam itself to that of its predators. So much information has been accumulated by the joint efforts of a number of investigators that it is only possible to discuss certain phases in this review. A number of general principles are of considerable importance and there seems to be some justification for considering some of the more important aspects of the problem.

It is a general biological principle that 90% or more of the food intake of any organism is expended in metabolic activity with less than 10% added as growth. For this reason, the mass of any population of predators represents less than one-tenth the mass of prey already eaten. Sawyer (1950) actually checked the relationship of food intake to growth in the clam drill, *Polynices duplicata,* and and found that the ratio was 20 to one on an average for all sizes. The author determined a ratio of nearly 5 to one for very young specimens of this species but their efficiency declined rapidly with growth.

There seems to be general agreement among investigators that most predators of commercial molluscs have a tendency to select small sized individuals for their prey. One reason seems to be due to the population structure of the predators. In most predator populations the young specimens far outnumber the older ones and these young predators have a tendency to attack molluscs below certain sizes. Similarly there seems to be a tendency for new generations of predators to appear simultaneously with the new generation of their prey. In some instances the predators appear without much visual evidence of adults in the vicinity. The Rutgers group of investigators has reported considerable difficulty in raising newly-set hard clams because of the predations of tiny drills (*P. duplicata*) even when the incidence of adults in the vicinity was low.

It has been somewhat of a puzzle as to how predators manage to survive when the apparent abundance of their prey, the commercial molluscs, is low. The investigations of Shuster (1950) on the horseshoe crab and Carriker (1951) on several predatory gastropods have shown that predators can utilize a variety of types of organisms which may sustain them in the absence of the commercial species. Carriker has shown that there may be a definite preference for a particular kind of prey and it follows logically that the predators of interest to the shellfish industry are the ones that prefer commercial molluscs.

It is unfortunate that continuous records of abundance of predators have not been kept. It is thus difficult to assess the importance of any one predator because the current abundance cannot be compared with former times. Certain of the predators reproduce by means of limited numbers of eggs and give some degree of parental protection during the developmental stages. This type of reproduction according to Thorson (1950) tends to maintain the species at a fairly constant level, which makes it seem likely that changes in populations of these predators would be slow and cover long periods instead of the violent fluctuations from year to year that are observed in other species.

Investigations of Glude (1953a) and his associates have given some indication that the green crab, *Carcinides,* has recently extended its range northward from Cape Ann to Eastport, apparently favored by a rise in certain critical seasonal temperatures. In this connection, the section of the extended range appears to have favored an enormous increase in the numbers of green crabs in the new environment although the population in the normal range appears to have remained constant. As pure speculation it may be suggested that the green crab has extended its range in advance of its own predators.

The natural history of predators and the interactions of their populations with those of the commercial molluscs could be discussed at considerable length. The predators are undoubtedly important factors in the limitation of the production of commercial molluscs and there is an enormous need for a complete understanding of their natural history.

AGE AT SEXUAL MATURITY

Many practical workers whose efforts are directed toward the improvement of commercial shellfish resources and the establishment of new ones consider the primary aim of their work to be the establishement of self-propagating populations in depleted localities. Thus there is considerable interest in the size and age at which many species become sexually mature, as well as the age at which the reproductive potential may be at its height.

Coe and Turner (1938) have shown that the soft clam may become sexually mature during its first summer, if the set occurs early enough and other conditions favor fast growth. Belding (1931) has estimated that the soft clam produces about 3 million eggs by the time it reaches a length of 2½ inches. Belding (1931a) has determined that the hard clam first matures during its second year and the egg production reaches 2 million when the female is 2½ inches long. He (1931b) has also determined that the hermaphroditic bay scallop spawns when one year old for the only time in its life with an egg production of approximately 2 million.

There is only moderate interest in the reproductive biology of the oceanic species because they are seldom transplanted for propagation. Belding (1909a) believed that the sea clam spawns when one year old but considered the first important spawning to occur in the second year. Posgay's observations on the sea scallop seem to indicate that sexual maturity is delayed beyond the second year.

A number of workers have held the opinion that the reproductive potential of a number of commercial molluscs reaches its height in the young adult and then declines with advancing age. There does not appear to be any information in the published literature that confirms this theory and the recent works of Loosanoff (1953) on the oyster and hard clam have demonstrated that the numbers of eggs increase with size of the female with no decline in their quality.

THE LIFE SPAN

The life spans of most commercial molluscs have not been determined with certainty. Belding (1931) has estimated that the soft clam may live for ten to twelve years and there are indications that the hard clam lives much longer. Belding (1931b) has shown that the bay scallop is an exceptional species which normally lives about 20 months although there are occasional specimens that survive their second winter and spawn twice. Nothing appears to be known about any of the other species.

Knowledge of the life expectancy of heavily exploited commercial molluscs is probably of little practical importance because it is unlikely that many ever die of old age. The matter becomes important only in the regulation of new fisheries or advising the industry as to what may be expected. In recent years, technological developments and market demands have made it possible to exploit the sea clam off Long Island and the soft clam in the Chesapeake Bay, both of which had been previously untouched. Since both the sea clam and the soft clam live for a relatively long period, there was an accumulation of generations which had been the result of several seasons' spawnings. In both cases the amount of material available was sufficient to justify considerable investment in boats and machinery while marketing and processing facilities were being developed to handle the material as fast is it was brought in. The natural reserve supply enabled the industry to operate in this expanded condition for a short time. However, the rate of utilization was considerably greater than the rate of replacement, and eventually the industry found itself loaded down with a heavy investment in equipment, and an inadequate supply of clams. A better understanding of the extent of the resources and the probable rate of replacement might have made it possible for the industry to restrict its investment or amortize its equipment in such a way that it could have adapted itself to a reduced but continuous supply.

THE ECOLOGICAL ASPECTS OF EXPLOITATION

Human exploitation of commercial molluscs may affect their population dynamics in much the same way as an additional predator. The human exploiter resembles the predator in that he is competing in the struggle for existence (economic) with his fellow exploiters for a commonly owned resource. It costs him nothing but his labor and equipment, and the harvest will go to a fellow competitor if he doesn't get it first. For this reason the activities of the clam digger differ considerably from those of the farmer or stock raiser whose enclosed resources are under a high degree of control. Attempts have been made to control the activities of the human exploiter by passing laws and regulations that are supposed to manage the resources so that they will produce the highest continuous yield. Whether or not this is accomplished depends on circumstances, but a survey of typical laws indicates that few legislative acts are based on the biology of the species that they are supposed to regulate.

It is of utmost importance that there be a clear understanding of the effect of human exploitation on the ecology and population dynamics of any commercial mollusc before intelligent regulation is possible. In the following sections an attempt will be made to discuss exploitation in relation to a number of aspects of the ecology of the commercial molluscs.

THE EFFECT OF EXPLOITATION ON THE STANDING CROP: It goes without saying that the removal of any quantity of commercial shellfish from a local population reduces the size of the population by an amount equivalent to the quantity removed. This obvious observation is made here because there seems to be some confusion in the minds of interested persons as to what the effect of this action really is. There appears to be something in the popular philosophy of conservation that makes it desirable to maintain the standing abundance of commercial molluscs at a continuous high level without taking into account the fact that an abundance of material is completely useless until it is either sold at the dock or eaten at the consumer's table. This point of view is thus completely unjustified unless it can be demonstrated that a high level of abundance favors continual productivity.

Little is known concerning the influence of the size of a population of commercial molluscs upon its environment in respect to its effect on the possible yield. The term "possible yield" as used here means the amount that can be removed per unit time so as not to exceed the amount replaced by setting, growth, and survival. It would be of considerable importance to determine whether any level of abundance influences setting either favorably or adversely. The influence of crowding on growth has been demonstrated, but it has never been determined whether growth is faster or slower in large populations than in small ones. There are indications that the predator problem is more serious in small populations than in large ones but the influence of interspecific competition has never been investigated. The solution of these problems might determine whether overfishing in the biological sense ever exists. If it could be shown that the possible yield (excluding the effect of fishing efficiency) varies with the size of the standing crop, it might be possible to regulate exploitation to maintain the abundance at an optimal level.

In this connection the term "depletion" is popularly used to describe the condition of a stock that has been reduced to such a low level that continued exploitation is no longer worthwhile. It must be kept in mind that the commercial molluscs make up a self-renewing resource which can be exploited only at a rate equivalent to the rate of renewal. Thus the removal of any accumulation does not cause any more of a depleted condition than occurs on a cattle range after the market roundup.

The reduction of the standing crop, however, has considerable influence on the efficiency of the fishing operations. Dense populations are easier to dig or dredge than light ones although the actual yield for any given time span may be the same, whichever level is maintained. The competitive nature of commercial shellfishing makes it very difficult to maintain the population density at a high level, although attempts at management by rotation of areas have been said to be successful. It is not certain that the total producion has ever been increased by this form of management, but the increase in efficiency of harvesting accumulated stocks appears to have had a favorable effect on the fishermen.

THE EFFECT OF EXPLOITATION ON PROPAGATION: It is popularly believed that any reduction in the standing abundance of a local aggregation of commercial molluscs reduces the reproductive potential and retards recovery to the former level. There is nothing in the published literature that indicates that this ever occurs in populations of organisms with reproductive mechanisms such as the commercial molluscs. It would seem logical that there should be a critical level below which propagation is affected adversely but such a level has never been determined. The possibility that a population may become so sparse that the separation of its constituents prevents fertilization of the eggs has been discussed in a previous section but there is no direct evidence that this ever occurs.

The author (Turner, 1951) has obtained some indirect evidence that overexploitation may adversely affect propagation in the soft clam. The soft clam resources in Massachusetts are distributed in the clean areas where digging is generally unrestricted and in contaminated areas where special licenses are required. Heavy digging pressure on the clean areas in the late 1930's exhausted the adult populations with subsequent failures of repopulation. The supplies in the contaminated areas, where the various restrictions held the digging pressure down, continued to produce and repopulate themselves.

If exploitation has an adverse effect on propagation there is some question as to whether it is a result of a smaller spawning population or some other factor. In this connection the idea of gregariousness developed by Cole and Knight-Jones (1949) deserves some discussion. Cole and Knight-Jones observed that European oyster tended to show a preference in setting for living oysters or shell containing some spat. They suggested that the presence of living metamorphosed oysters attracted the larvae about to metamorphose by some unknown mechanism. They also found some evidence that a few living oysters placed in a bed of cultch appeared to increase the intensity of the set although the parent stock was known to be outside the bed of cultch. The author (Turner, 1949a) has suggested that such a mechanism might apply to both the hard and the soft clam on the basis of casual field observations that young specimens often occur near older ones but the evidence is inconclusive. If the gregarious tendency is common to all molluscs, the excessive depletion of an adult stock might reduce the intensity of setting.

In the final analysis there is no direct evidence that exploitation has any real influence on propagation of commercial molluscs. The evidence that excessive exploitation affects propagation adversely is both indirect and tenuous and needs further study.

THE EFFECT OF EXPLOITATION ON THE POPULATION STRUCTURE: The effect of exploitation on the population structure depends on the selectivity of the gear, destructiveness of the gear, and on certain market preferences. Surveys by the author and his associates have shown that soft clam populations of Boston Harbor have a tendency to be made up of specimens less than two inches long, the larger ones being continually removed. The exact effects, however, appear to be modified by the composition of the population before exploitation. The erratic setting behaviour and dominant year class phenomena tend to produce local populations with a variety of structures, each of which may be modified in a different manner.

Glude and Landers (1953) have shown that the selectivity of the gear has a considerable effect on the way hard clam populations are modified by fishing. Hand gear such as bull-rakes and tongs are relatively unselective and fishing with these implements tends to reduce equally the abundance of all sizes above the legal minimum size. Dredges, on the other hand, are selective for the larger specimens and release the smaller ones.

THE EFFECT OF EXPLOITATION ON THE SUBSTRATUM: The process of removal of commercial molluscs disturbs the substratum to some degree. Burrowing species are excavated with forks, rakes, dredges, hoes, and tongs, all of which agitate the sediments. The removal of attached forms with scrapers and dredges disrupts the community and may even alter or remove the attaching surfaces

It is impossible to evaluate the significance of these modifications because no important measurements have been made. Various suggestions have been brought forth as to the possible beneficial effects of ventilating the soil and discouraging unwanted growths, but these are a result of pure speculation.

The effect of various methods of exploitation of commercial molluscs is of considerable importance because it determines the kinds of laws that might benefit the various fisheries. It is a subject of much controversy, most of which is conditioned by social and economic competition between groups with the conservation angle brought in as a reason. The essential part of the controversy revolves around the question as to whether it is more beneficial to permit intensive exploitation by a few who can afford the high costs of efficient machinery or to spread the resources among a larger group who can make a prolonged occupation by eking out a marginal existance with inefficient hand tools. An additional question arises as to whether a better yield is obtained in the long run by the continuous working over of an area in a random fashion or by the rotation of subareas to allow time for repopulation and growth.

The question of the effect of power dredging versus bullraking has been intensively studied by Glude and Landers (1953) in the hard clam fishery of Rhode Island. These investigators have concluded that there is no biological basis for restricting either method although they made the point that social, economic, and legal aspects of the problem were not taken into consideration during the investigation. These findings mean that management authorities may be perfectly justified in restricting methods of fishing to comply with social needs but there is no occasion for justifying such actions by claiming that there is a biological basis.

THE PROBLEM OF SHELLFISH FARMING

The possibility of farming various kinds of commercial molluscs has attracted considerable attention for some time because of the extraordinary rate of production observed in isolated instances. The Rowley Reef set of soft clams, as a typical example, matured in approximately two years and produced over 1,000 bushels or nearly 15,000 pounds of soft clam meats on a little over an acre of ground. Such instances have been taken as an indication of the potential productivity of the coastal flats as a whole and the idea has been held by a number of investgators that almost any area could be made highly productive with a little help from man.

The important steps in successful farming involve populating an area, maintaining satisfactory growth and survival, and harvesting the crop in an efficient manner. The complex life history of the commercial species makes each one of these steps difficult to accomplish in a practical way.

POPULATING THE AREA: Experimental farming of the soft clam was carried out in the early part of the century by Kellogg (1903), Mead (1900-04), and Belding (1909). Kellogg, working in the Cape Cod region, populated his experimental areas by collecting small clams from various parts of Buzzards Bay. The clams were then spread over the surface of the experimental beds where they dug in. Belding, who operated in much the same way, took advantage of various "super-sets" and devised methods of screening the tiny clams out of the sand. Mead likewise depended on natural populations but also invented an ingenious spat trap which consisted of a box of sand covered with a coarse mesh screen. According to Mead's theory, larvae swimming against the screen would retract their motile organs and sink into the box. The device was reported to be very successful

The chief drawback to these methods of populating an area lies in the cost of the operation and the uncertainty of the supply. Super-sets occur only sporadically and there is a general popular resistance and in some cases legal restrictions to the taking of small publicly-owned shellfish for private profit. Even Mead's spat traps could hardly be depended on to supply enough raw material to populate a farm of reasonable size.

The author (Turner, 1948) and later Smith (1950) attempted to devise methods of populating barren areas by altering the substratum in a number of ways to induce setting. Some success was obtained by resurfacing with march sods, covering the flats with plastic mesh, and stretching out old netting. It was later shown by Smith (1952) that these structures merely concentrated wandering juvenile clams and the numbers obtained were insufficient to be practicable on a large scale. Thus at the present time there appears to be no simple, inexpensive, practical way of populating barren areas with soft clams. The same holds for the hard clam but there appears to be less interest in hard clam farming. In this connection it should be pointed out that a number of so-called hard clam farms are in operation at the present time. These cannot be considered farms in the true sense of the word because they are merely holding grounds for clams purchased when the price is low to be sold when the market improves. They are also used as decontamination areas where clams taken from polluted localities under special permit may be held for purification.

MAINTAINING GROWTH AND SURVIVAL: Readers of Kellogg (1903), Mead (1900-04) and Belding (1909) are generally so impressed by the successful pilot-plant experiments reported by these investigators that little consideration is given to the experiments that failed. Recent investigations by biologists of the U.S. Fish and Wildlife Service, the State of Maine, and by the author have shown that an overall average growth and survival of soft clams in a number of selected areas in Massachusetts and Maine are inadequate to put soft clam farming on a paying basis. The general opinion held by all investigators who have attempted to farm soft clams experimentally at the present time is that survival is so adversely affected by predation that there is little opportunity of bringing a crop to maturity before it disappears entirely. It has been universally observed that soft clam farms exert an attraction to a number of species of predators which tend to concentrate on the populated areas. It is interesting to note that this baiting attraction seems to affect predators of different groups and over a wide geographical range. In Southern Massachusetts the boring snail *Polynices duplicata* and the horseshoe crab *Limulus polyphemus* are the chief offenders. In Northern Massachusetts the horseshoe crab and the green crab *Carcinides maenas* have caused the greatest damage. In Maine the chief complaint is against the green crab. The Canadian Maritime Provinces are just beginning to experience an invasion of the green crab, according to latest reports, but the predations of the small boring snail, *Polynices triseriata*, has been sufficient to prevent profitable farming of the soft clam in many localities.

It would seem from analysis of the history of the Rowley Reef set and the Raccoon Island set (Turner 1953) that the predator-prey relationships and other factors influencing the survival of the soft clam are such that circumstances permitting profitable farming of this species are rarely encountered. In both of these sets the numerical survival at the time the crops approached maturity was considerably less than 1%. It is thus evident that any farming venture starting with transplanted material will have to depend on growth of considerably more than one hundred fold if the above mentioned conditions are of common occurrence.

THE IMPORTANCE OF METHODS OF HARVESTING: One of the greatest difficulties in the economics of shellfish farming that is seldom considered is that conventional methods of harvesting are costly. Even when the problems of propagation and survival are solved, it will be necessary to develop efficient methods of harvesting in order to compete with the free digger. In the case of the soft clam, the digging is usually done with a thined hoe. The work is back-breaking and the diggers are conditioned to thinking on a piecework basis exclusively. At the present time they would not consider employment in harvesting a shellfish farm at much less per bushel than they would expect to be paid for clams obtained from a public digging area. Thus the owner of the farm would find that the labor costs of removing clams from his bed by conventional methods would be so close to the market value that the operational overhead would more than cancel the profits.

Two devices operating on the jet principle have been invented recently which offer promise in making the harvesting of soft clams and other species efficient. A simple machine consisting of a skiff equipped with a centifugal pump and an A-frame at the stern has been used successfully in Martha's Vineyard for some time. The A-frame supports a number of pipes connected to the pump. These are lowered into the sand and water is forced under high pressure to jet the clams to the surface. One operator pushes the boat along through shallow water while another follows along and gathers the clams with a scoop. At present prices the entire apparatus would probably cost about $200-$300 for new materials. A satisfactory device could undoubtedly be built out of second-hand parts for considerably less.

A more elaborate device has recently been developed in the Chesapeake Bay for harvesting soft clams in as much as six feet of water. This apparatus consists of a large self-propelled scow with a notch in the forward end. A conveyor belt of flexible grill work extends through the notch to the level of the bottom. A series of jets supported by an A-frame and supplied with water under high pressure from a deck pump are situated just ahead of the conveyor. In actual operation the conveyor is lowered to the bottom and the jets are turned on. As the scow moves forward slowly the jets wash the clams out of the mud and the conveyor picks them up and carries them to the deck. The apparatus is extremely efficient in its ability to collect practically all the clams in its path and bring them unbroken to the deck. Its use is limited to muddy or sandy soils however because it collects stones and pebbles as efficiently as it collects clams. Destruction of clams of small size is prevented by adjusting the mesh of the grillwork of the conveyor to permit the small ones to fall through before they reach the deck. One of the owners of such a digging machine estimates that the cost of the apparatus was approximately $8,000.

THE OUTLOOK ON SHELLFISH FARMING: The experience gained within the past few years does not appear to forecast a bright future for profitable farming of commercial molluscs. There is little doubt, however that primitive man reached the same conclusion a number of times when he first attempted to bring wild food resources under some degree of control. It is easy to imagine the chagrin of the early crop grower when his crude garden attracted swarms of insects or his small herd was wiped out by hungry predators or unaccountable diseases. Nevertheless, centuries of accumulated experience and technological advances have made it possible to produce food on land on a scale far beyond the wildest dreams of the first man who thought of planting a few seeds on a patch of bare ground.

Only a little more than fifty years have elapsed since Kellogg, Mead, and Belding attempted to introduce the farming of soft clams and laid the groundwork for future developments by describing the natural history of the species. Meanwhile the economic needs for advancements along this line have been insufficient to support or encourage further developments until the last decade so that the necessary knowledge and experience is thus still in a primitive and inadequate state. However, a vast quantity of information has been accumulated on the factors that prevent profitable farming of commercial molluscs. The understanding of these factors opens up the possibility of overcoming them so that great advances may occur in the not too distant future.

CONCLUSION

An attempt has been made to restrict the scope of the foregoing review to the aims of the co-operating investigators and to cite only such material as might pertain to the problem of increasing the availability of the commercial molluscs to man. In following this course it has been necessary to eliminate a wealth of material that might justifiably deserve more extensive consideration. Investigators in all branches of the biological sciences have found various commercial molluscs to be convenient experimental material because of their size and availability, and papers dealing with systematics, anatomy, embryology and physiology are scattered through journals published in almost every language. In the field of physiology alone Scheer (1948) cites 126 references for the Phylum Mollusca, with only the important papers mentioned. It is often difficult to see the connection between the results of an isolated physiological experiment and the problem of increasing production, but it is becoming increasingly clear in all branches of biology and medicine that no bit of information can be considered insignificant.

Mention should also be made of the possible disadvantages brought on by the restricted nature of the present investigations. The term "commercial mollusc" is an artificial one and as such, tends to prevent investigators from paying adequate attention to related species from which valuable information might be derived. Each species of commercial mollusc occupies a definite ecological niche which it shares with a host of other organisms including not only the non-commercial molluscs but also a variety of filter-feeding sedentary invertebrates. In general these unwanted forms have received less attention than the weeds in a garden except for the rare instances in which their populations have become so prominent that they have appeared to be obvious competitors. It may be suggested that any information pertaining to sedentary filter-feeders may have some indirect or direct bearing on the biology of the commercial molluscs and no aspect of their biology is too insignificant to be neglected.

Two groups of molluscs of minor commercial importance have not been considered. In the introductory passages mention was made of the gastropods (snails) for which there is a small market in the large metropolitan centers containing various groups of recent European extraction. In addition the cephalopods which include the squid, octopi, and cuttle-fishes are of considerable importance both as human food and as bait. However, their mode of life is so different from that of the sedentary molluscs that any problems arising in connection with their fisheries would come under the catagory of pelagic fisheries problems and methods pertaining to the sedentary forms would not apply.

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Contribution No. 716

Särtryck ur Tellus nr 4, 1954

On the Structure of Some Cumulonimbus Clouds which Penetrated the High Tropical Troposphere[1]

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(Manuscript received 25 May 1954)

Abstract

Some extremely large oceanic trade-wind cumulonimbus clouds extending upwards of 40,000 ft into a region of strong winds and intense vertical shear have been studied by means of time-lapse photography. A simultaneous still picture of the clouds taken a known distance and direction away from the motion pictures permits triangulation upon the clouds and calculation of the vertical and horizontal motions of several of the individual towers. By means of a nearby radiosonde observation, it is established that the air forming the strongest of these towers must have risen from near cloud base with little or no dilution of its buoyancy by mixing with the clear-air surroundings.

The model of Malkus and Scorer (1955) concerning the erosion of cumulus towers is reviewed and tested upon these towers with satisfactory results. A minimum horizontal cloud dimension is apparently required for the production of undiluted towers. The horizontal motion of the clouds relative to the air is also estimated from the model and tested by the observations and the net upward transport of latent heat in water vapor is calculated approximately.

1. Introduction

Recently it has been found possible (Malkus and Scorer, 1955) to formulate quantitative laws for the rise and decay of individual cumulus towers and to describe their time dependence in terms of relatively few parameters. So far, however, most of the observations used to check the theories on cumulus have been made upon rather small, non-precipitating trade-wind clouds, which have been ascending through air masses exhibiting fairly weak wind shear. Large, precipitating cumulonimbus have proved somewhat formidable to investigate by means of aircraft, especially when accurate vertical draft measurements are desired. Fortunately, the new theoretical model of cloud towers is well suited to testing by measurements from time-lapse motion pictures, with a minimum of additional information, including a nearby clear-air temperature sounding. The present paper is a study, based on time-lapse photography, of some oceanic trade-wind cumulonimbus clouds whose towers penetrated heights exceeding 40,000 ft and wind shears

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[1] Contribution No. 716 from the Woods Hole Oceanographic Institution.

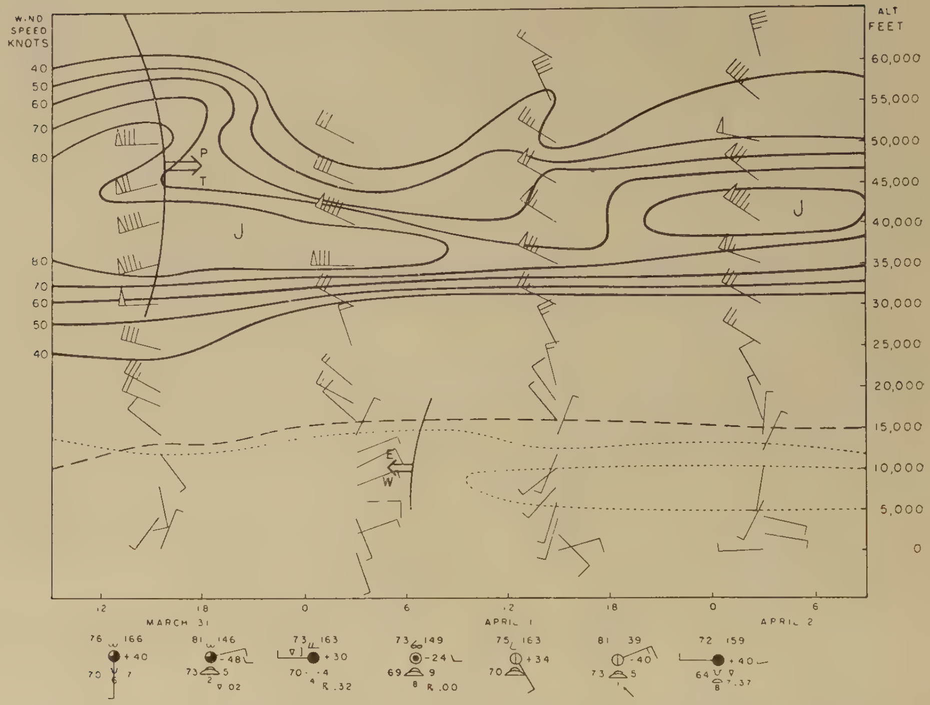


Fig. 1. Time cross section for San Juan, Puerto Rico, from 1200 GCT, March 31, 1953 to 0600 GCT April 2, 1953. The ordinate is height in feet. Winds are plotted in knots, a short barb indicating 5 knots, a long barb 10 knots, and a solid triangle 50 knots. The solid lines are isotachs of wind speed, drawn every 10 knots, with J indicating maxima. The dashed line indicates the base of the westerlies, and the dotted line shows the top of the moist layer. The heavy solid line marked PT indicates the polar trough which passed San Juan moving eastward on March 31, and the solid line marked EW denotes a weak easterly wave which passed San Juan moving westward early on April 1.

as high as 30 mps/km. In addition to testing the theory in this rather extreme case, some mportant differences between large and small trade cumulus are brought out which may be nterpreted by means of the model.

These data were taken on April 1, 1953, during a joint observational program in the Caribbean carried out by the meteorological group from the Woods Hole Oceanographic nstitution and the Department of Meteorology of the Imperial College, London. Throughout this program, two main observation points were used, the first being the small, lat West Indian island of Anegada (18°50′ N, 64°20′ W; dimensions two by ten miles) and the second a PBY-6A aircraft, equipped as a meteorological tool, which was flown n the near vicinity. Supplementary information, such as radiosonde and radiowind data, was obtained from the U.S. Weather Bureau at San Juan, Puerto Rico (120 miles west-southwest from Anegada). The cumulonimbus clouds on this occasion were photographed by a time-lapse camera mounted on the beach at Anegada, and sufficient additional information was available to permit numerous calculations from the films. After a brief description of the prevailing meteorological conditions and the equipment and techniques used in the measurements, the major portion of this paper will be concerned with these calculations and their interpretation.

The synoptic situation on April 1 was dominated by the passage on the preceding day of a strong polar trough. In the Caribbean area, the low-level easterlies were overlaid by westerlies beginning at 15,000 ft elevation. These westerlies were concentrated in a shallow, high-tropospheric layer with maximum speeds of 100 mph at an elevation of 40,000 ft. The sequence of events is illustrated in the time cross-section for San Juan shown

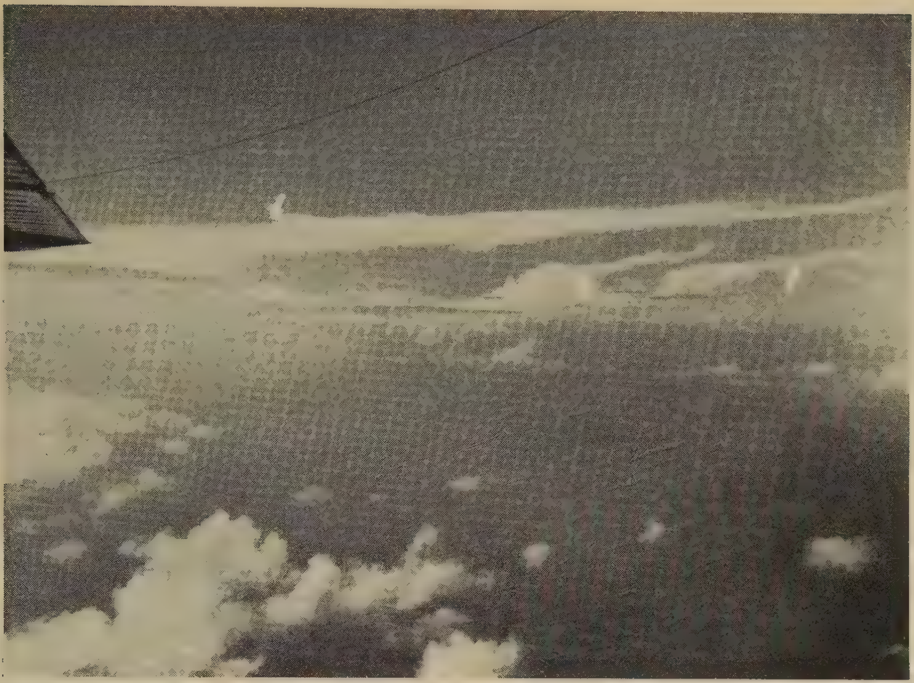


Fig. 2. Still photograph from the PBY showing the clouds studied. The arrows indicate the points upon which triangulation was performed. The aircraft was being flown at 6,000 ft toward 293° True and its location is given in Figure 5.

in Figure 1. At the time of the present observations, 1220—1345 LST (1620—1745 GCT) the region was dominated by the northwesterly flow to the rear of the trough. By this time the overcast associated with the disturbance had broken sufficiently for several huge cumulonimbus clouds to be observed and photographed from Anegada. Fortunately the same clouds were simultaneously photographed with a still camera from the PBY, which was a known distance and direction from Anegada. Triangulation therefore permitted calculations of the distances, heights, and sizes of the clouds and their alteration with time from the motion picture film. The resulting vertical and horizontal motions could then be compared with the high-level wind and radiosonde observations (which were taken at 1500 GCT by the Weather Bureau at San Juan) and with the relations prescribed by the model.

II. Methods of Observation and Calculation

The time-lapse motion picture camera on Anegada was a Bolex 16 mm, equipped with an extreme wide-angle (58.3° horizontal, 44.3° vertical) lens. Exposures were made automatically at the rate of one frame every 3.6 seconds or 1,000 frames per hour. The camera was mounted on a tripod and aimed toward 22° from true North during the entire run.

The still camera in the PBY was a conventional Speed Graphic (50.0° horizontal, 42.0° vertical) which was mounted on gimbals so that it always remained level and was pointed at right angles to the fuselage. At the time the still pictures of the clouds were taken (1325 LST) the aircraft was flying at 6,000 ft elevation toward 293° True and was making a speed of approximately 130 mph over the ground. Since it was observed over Anegada on this heading at 1314 or 11 minutes earlier, a base leg for triangulation purposes of 24 miles is obtained. This distance was checked by additional knowledge of the time when the aircraft reached a location due north of San Juan. The base leg derived thus by interpolation came out 23 miles or within 5 %. Correction of the base leg for wind

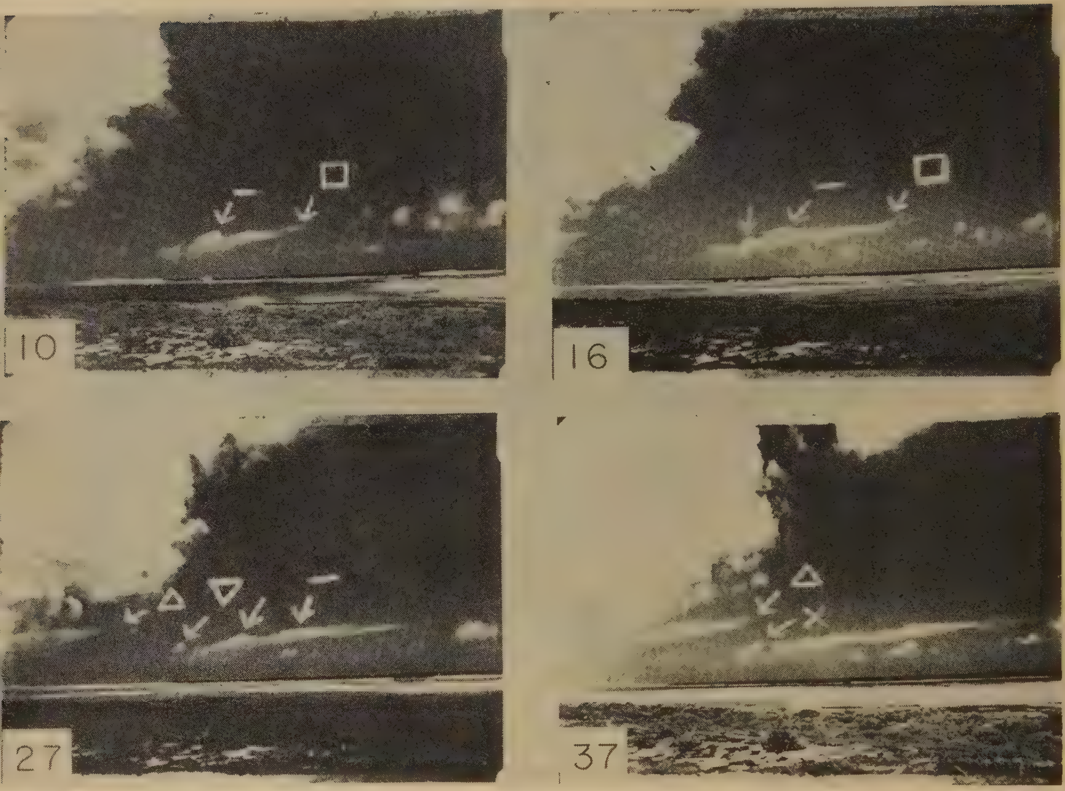
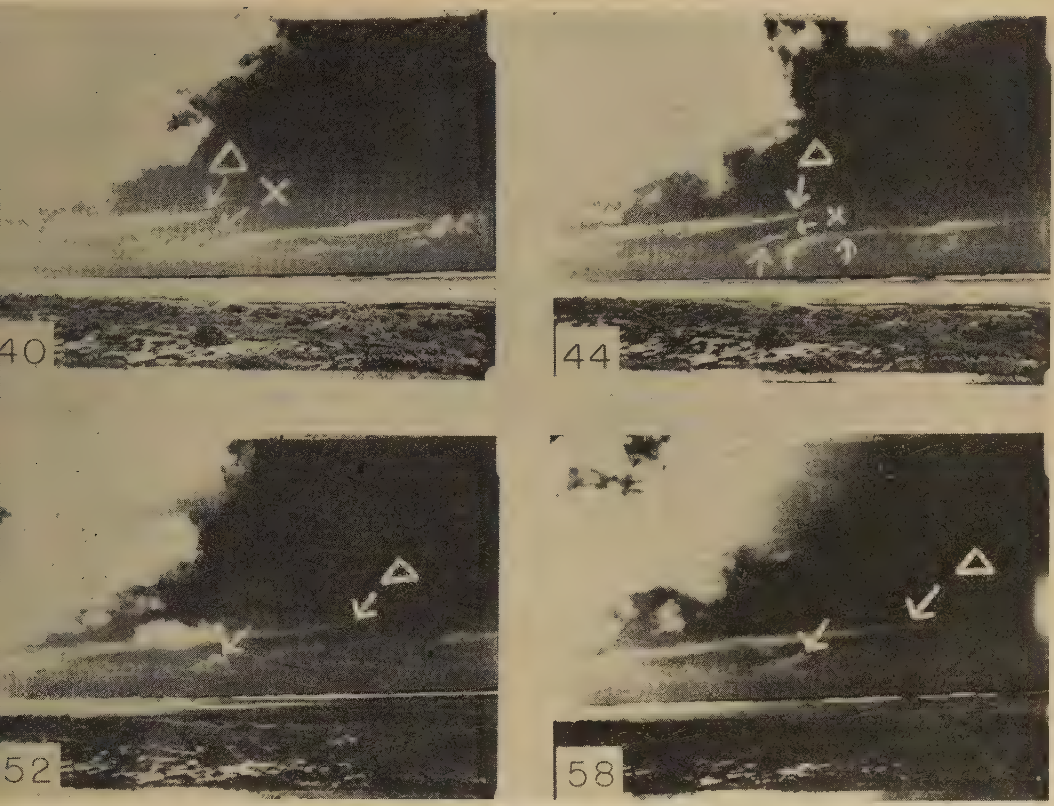


Fig. 3. Selected prints from the time-lapse motion picture run used in the calculations. The individual towers studied are denoted by the arrows with symbols above. The bubble followed on Tower Y (one of the strongest) is shown by the horizontal line; Tower W (finishing its cycle at the beginning of the run and therefore not included in the six towers studied) is indicated by the square; Tower C (weak) is shown by the arrow alone; Tower Q (weak) is denoted by the inverted triangle; the streamer on Cloud II is marked by the erect triangle (used only as a check in the calculations); and Tower X (strong) is indicated by an X. The camera was mounted on the beach at Anegada and pointed toward 22° True throughout the run. The print number is given beneath each frame and consecutive prints were 1.2 minutes apart (every 20 frames of the motion picture film, which was exposed at the rate of one frame every 3.6 seconds).

drift of the aircraft was made, but was negligibly small.

Figure 2 shows the Speed Graphic (PBY) photograph used in the triangulation. The time-lapse pictures were printed at intervals of 1.2 minutes, and the prints numbered from the beginning to the end of the run (1—58). Selected prints from this series are reproduced in Figures 3 and 4. Print 44 was picked as the frame coincident with Figure 2. Triangulation was first performed for the three points marked with inverted arrows (on Figure 2 and Print 44) on the far cloud, hereafter to be called Cloud I. The angle of each point from the optical axis of the camera was found by using the proportional distance of the picked point from the center to the edge of the negative. The half-width of the negative and focal length of the lens were accurately known and these gave the tangent of the total half-angle covered by the camera.

Results of this and a similar triangulation on one point on the near cloud (called Cloud II) are shown in Figure 5. By laying out two angles for each point at the ends of the base leg on a scaled map, it was determined that the three points in Cloud I lay not only in a straight line but almost exactly parallel to the image plane of the motion picture camera (i.e. in the plane of the photographs) and a perpendicular distance from it of 78 miles. The point on Cloud II was a perpendicular



ig. 4. Additional selected prints from the motion picture camera on Anegada. On Print 40, Tower P (weakest ɔwer studied) is shown by the arrow alone; Tower X is indicated by an X, and the streamer on Cloud II by an ect triangle. Print 44 was the one used in triangulation (compare to Fig. 2). The arrows alone indicate the points iangulated upon (see results in Fig. 5). The arrow alone on Prints 52 and 58 (the last one in the run) shows Tower R. The dissipation of the entire cloud mass may be noted on the last print.

istance of 66 miles from the image plane. fter discussing the possible errors in triıgulation, we may carry out calculations om this point forward using the motion icture frames alone.

In the case of Cloud I, for which all the gnificant calculations were performed, the nage location never exceeded an angle of 10° from the optical axis, hence errors in stances and separations due to distortion by ie lens may be totally neglected compared to rors in triangulation. An error of 2.2 miles the base line (9 %) would give an 8 % ror in the distance to Cloud I, and it is oubtful that the error in the base line was is great. The largest source of error lies in e determination of the angles. A 2° error any one of the angles would produce a 7 mile or 9 % error in distance to Cloud I. All the angles save one may be shown reliable within this accuracy. The greatest uncertainty lies in the angle between the optical axis of the Speed Graphic and the heading of the PBY, which was adjusted to 90° by sighting along the trailing edge of the wing (fortunately constructed at exactly 90° to the aircraft axis). That the errors in angle were very small, however, is suggested by several independent checks upon the triangulation. The first is that all three points on Cloud I lie in a straight line along the plane 290°—110°, as an analysis using the wind profile shows must be the case. The second is that triangulation gives horizontal separations on the map between these points departing by much less than 10 % from the separations measured

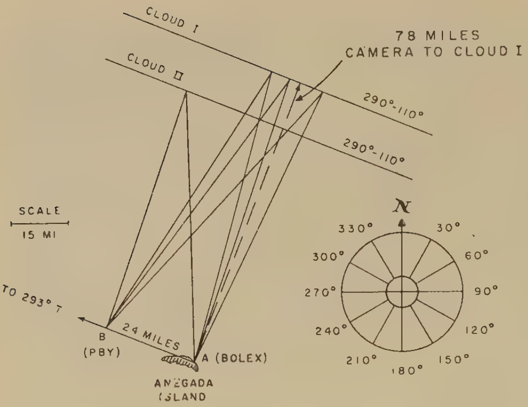


Fig. 5. Scaled map showing results of the triangulation using Figure 2 and Print 44, Figure 4. The camera on Anegada was located at A, pointing in the direction of the dashed arrow (toward 22°). The PBY was located at B, heading in the direction indicated by the solid arrow. The three points indicated by arrows on Cloud I (Fig. 2 and Fig. 4) lie along the line marked "Cloud I" which lies very closely in the plane 290°—110° and 78 miles perpendicular distance from A. The single point triangulated upon in Cloud II lies 66 miles perpendicularly from the plane 290°—110° through A.

on the photographs, using the derived distance to the camera of 78 miles. The final check is that triangulation on Cloud II gives its heights and velocities as extremely close to those of comparable portions of Cloud I.

The vertical angular distance (on Print 44) between the horizon and the farthest left point on Cloud I is determinable from the ratio of this distance to the vertical half-width of the negative and knowledge of the focal length of the lens. Using the horizontal distance of 78 miles and the tangent of this angle, the vertical elevation of this point above the horizon was found to be 27,000 ft or 8.24 km. This length could then be used as a basic distance scale for the calculations to follow. In order to obtain the elevation of this point above sea level, however, a correction had to be introduced due to the curvature of the earth. For a distance of 78 miles, this proved to be 4,000 ft or 1.2 km. In presenting actual altitudes of all points on Cloud I, this correction has been added.

In order to apply the distance scale obtained from Print 44 to other parts of the cloud and to motions of portions of the cloud towers throughout the entire 70-minute run, it was first necessary to ascertain whether the cloud had any component of motion into or out of the plane of the photograph and whether it might develop any slope normal to that plane. Inspection of the San Juan radio-wind observation (see Figures 1 and 9) shows that the wind directions throughout the height range of the calculations (30,000—47,000 ft) departed rarely, and never more than by 10°, from the plane of the photographs. Although the wind departed significantly from this direction at lower levels, it may be shown by consideration of even the minimum drag forces ordinarily acting on cumulus that the component of cloud motion normal to the photographs should have become vanishingly small by 9.5 km. Thus the cloud, which was shown by triangulation to have no significant slope perpendicular to the plane of the photographs on Print 44, should not develop any such slope with time, nor should it move any appreciable distance toward or away from the camera during the 70 minutes considered. The distance scale for Print 44 was therefore used throughout without correction, with extremely consistent results.

III. Basic Features of the Major Cloud

The main dimensions of Cloud I are now readily obtainable from Print 44. At 31,000 ft (9.5 km), the width of the left-hand tower (containing the left-most point triangulated) is 20,500 ft or 6.3 km. The greatest elevation above sea level attained by any portion of the cloud is reached by the streamer extending out to the right, which achieves a maximum height of about 15.3 km or 46,600 ft and a horizontal extent of 45 miles. The striking feature of this cloud's changes with time on Prints 1—58 (70 minutes) is its production of six successive towers, each of which is seen to rise vertically, spread laterally into a long streamer and then dissipate gradually. The towers were found to vary widely in their dimensions, maximum ascent speeds, and heights penetrated. The two most vigorous towers are marked by a horizontal line and an X on the prints shown in Figures 3 and 4. A typical one of the weaker towers is denoted by the inverted triangle. It is important to note that each of these towers underwent an initial period of rapid rise which petered out into a period of much slower rise some-

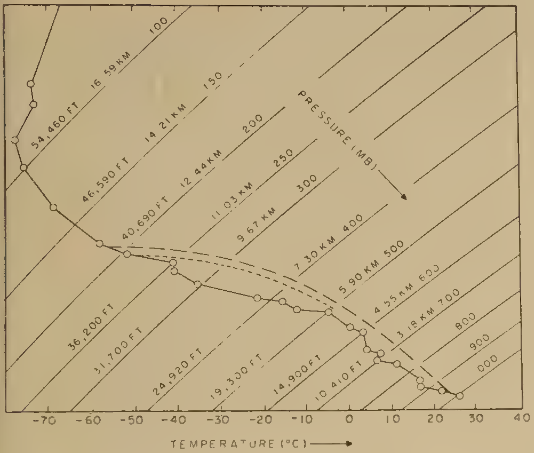


Fig. 6. Tephigram showing San Juan radiosonde observation, 1500 GCT, April 1, 1953, reduced from the original data[1] to obtain more closely spaced points than that of the teletype transmission. The sounding is given by the solid line. The dashed line is the moist adiabat intersecting the sounding at cloud base (950 mb) used to obtain the buoyancy for the strongest bubbles, and the dotted line is the moist adiabat used in obtaining the buoyancy of some of the weaker bubbles.

where between about 11.0 km and 12.5 km (or about 3—5 minutes after the tower first emerged from the main cloud mass). The period of slow rise averaged about 10 minutes, while another 10—15 minutes elapsed, in general, during the dissipation of the streamer. In the case of the two most vigorous towers, close inspection of the films reveals that the transition from rapid to very gradual ascent took place near 12.6 and 12.2 km, respectively, where the appearance of the towers also changed markedly and sharp outlines became lost. This transition could be in no way related to the transition between supercooled water and ice crystals which must have occurred at no higher than 10.9 km, where even a maximally buoyant cloud element reached −40.0° C.

The San Juan radiosonde observation for 1500 GCT is reproduced in Figure 6. The sounding has a most striking feature. It shows that any cloud element which is finally to reach the vicinity of 12.5 km with vanishing (and not negative) buoyancy, must have risen moist adiabatically and undiluted all the way from cloud base at 950 mb. Any mixing or dilution by the clear-air surroundings on the way up, even a small fraction of that encountered by STOMMEL (1947), MALKUS (1952, 1954) and others in smaller trade cumulus would have resulted in prohibitively large negative buoyancies at this level. The next section is intended to shed light on this point.

IV. The Erosion and Life Cycle of the Cloud Towers

a. *The model to be used.* — MALKUS and SCORER (1955) showed by theoretical and observational argument that the tops of actively rising cumulus towers should obey the following differential equation:

$$\frac{dw}{dt}+Kw^2=gB \qquad (1)$$

where w is the ascent velocity of the tower; K is a drag coefficient to be specified presently; and gB is the buoyancy acceleration which is given by $g\left(\frac{T_v-T_v'}{T_v'}\right)$ minus a correction for suspended hydrometeors, where T_v is the virtual absolute temperature within the tower and T_v' is the virtual absolute temperature of the surroundings. The Kw^2 term represents the drag exerted by the surrounding air upon the tower and has been called form or profile drag by aerodynamicists. When it is small or zero, equation (1) returns to the familiar equation for the non-interacting buoyant parcel. When the vertical acceleration dw/dt, hereafter called $\dot{w}$, becomes zero, the buoyancy and drag are balanced and define a limiting velocity, w_L, which is given by

$$w_L=(gB/K)^{\frac{1}{2}} \qquad (2)$$

The drag coefficient, K, may be shown by dimensional argument to be inversely proportional to a linear dimension of the tower element; thus, the time dependence of some linear dimension must be specified in order to proceed further with the differential equation.

In obtaining an expression for K, MALKUS and SCORER (loc. cit.) have attempted to construct a model of cloud towers which permits physical interpretation of some of the

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[1] The writers are grateful to Dr. Herbert Riehl and Mr. José Colon of the University of Chicago for obtaining and reducing these data and also those for the radiowind observation in Figure 9.

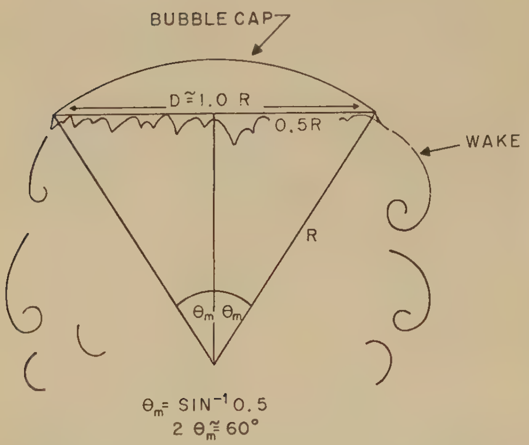

Fig. 7. Schematic diagram of a single buoyant element, showing the bubble cap with rounded upper surface followed by a turbulent wake. The radius of curvature of the cap is denoted by R and the cap diameter by D. The angular half-aperture is Θ_m which is by definition equal to $\sin^{-1} D/2R$. For the cloudy bubbles studied by MALKUS and SCORER (1955), D and R were no the average nearly equal, as shown here. This also proves to be the case for the large elements in the present study.

processes at work. They have envisaged a cumulus tower to be composed of one or more of the bubble-like elements shown schematically in Figure 7. Each element is hypothesized to consist of an undilute cap (which rises moist adiabatically) and a trailing turbulent wake. The upper surface of the cap is maintained quasi-spherical and its lower surface is flattened and irregular. The turbulent wake consists of moist air shed from the cap and drier air incorporated by entrainment from the surroundings. Using this model, equation (1) may be derived fairly rigorously and it may further be shown that

$$K = \frac{9}{4R} \tag{3}$$

where R is the radius of curvature of the rounded cap. The only crucial assumptions are that the actual ascent velocity, w, of the cap departs only little from the limiting velocity, w_L, defined by equation (2) and that the cap retains its shape (or ratio of diameter D to radius R) during its lifetime. Both of these assumptions are justifiable theoretically if the rate of decrease of R with t (supposed due to shedding of the outside layer of the undilute cap into the wake) is sufficiently slow and observationally they have been supported by measurements upon towers of small and medium-sized cumulus clouds. Alternatively, the theory so far can be derived by analogy with work on air bubbles in liquid performed by DAVIES and TAYLOR (1950).

In the case of cumulus towers it was found that the relation

$$R = EgB(-t) \tag{4}$$

could be made plausible physically and that it fit the available observations well. Malkus and Scorer called equation (4) an erosion law, where E is a constant of proportionality called the erosion constant, to be discussed presently, and t is chosen equal to zero when R becomes equal to zero and is negative during the element's active life. Equation (4) was only derived accurately for the case in which gB, the buoyancy of the element, was constant: that is for a wet-adiabatic environment. Combining (4), (3), and (1), and solving for a constant proportional to E, we have

$$\frac{3}{2} E^{-\frac{1}{2}} \equiv G = \frac{(-t)^{\frac{1}{2}}\, gB\,(1 - \dot{w}/gB)^{\frac{1}{2}}}{w} \tag{5}$$

If the hypothesized laws are valid, $\frac{3}{2} E^{-\frac{1}{2}}$ or G should be a constant for all cloud tower elements which are sufficiently isolated to be treated as individual bubbles. Equation (5) is ideally suited to testing by calculations from time-lapse motion pictures, if the buoyancy gB is known or can be estimated with the aid of a clear-air sounding and if it does not vary too rapidly with time. It was shown that (5) could be used with varying values of buoyancy provided that gB did not change by more than about 1/3 in 100 sec. An increase of buoyancy at this rate might overestimate G by as much as 20 %. It should be emphasized that from the level of their formation upward, the cloud bubbles are hypothesized to be rising along a moist adiabat. The mixing with the environment is achieved by erosion and the core of the cap remains undiluted until its final disappearance. The cumulus bubbles already studied were found to originate at different levels, some over land forming at or near the ground, others at cloud base, and still others up to the highest level within the cloud where the external lapse rate exceeded moist adia-

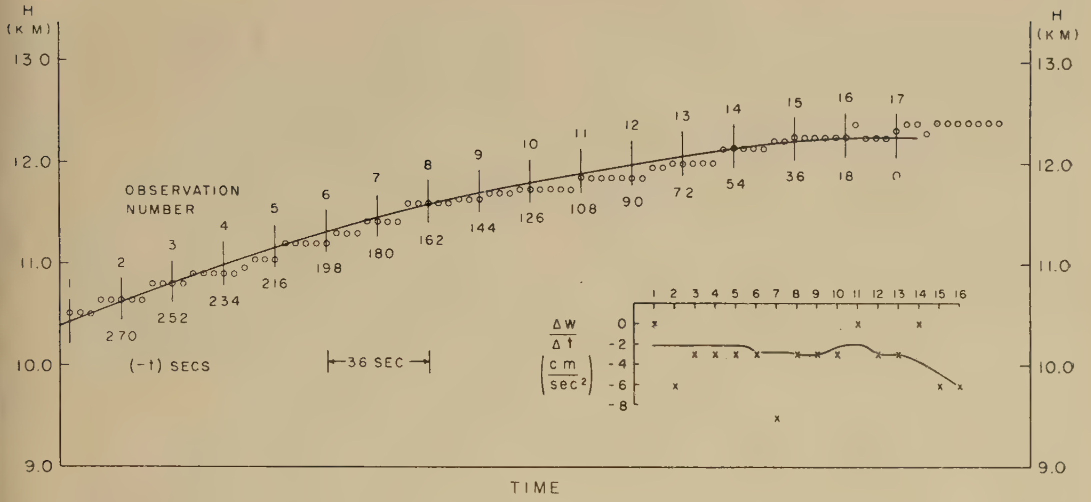

Fig. 8. Height of top of bubble in Tower X in km as a function of time in seconds. The time, —*t*, is chosen as zero when the bubble levels off and begins to appear in fuzzy outline on the film. Several points commonly occur on the same horizontal because readings could be made only to the nearest 0.05 cm on the microfilm viewer. Readings were made both in a forward and backward direction on the film and were found to coincide to this degree of accuracy. Velocities were obtained by reading first differences of the heights and were checked by average values read from the prints. Accelerations were obtained by taking second differences in heights (see inset graph) and were checked by taking first differences in velocities. The calculations made from these curves are presented in Table I.

batic. No oceanic trade cumulus bubbles have been found which originated below cloud base. The ones formed at higher levels were generally composed of smaller bubbles plus wake material, and thus were more "dilute" or had less buoyancy than those forming lower down.

The tests of the model performed by Malkus and Scorer upon small and medium-sized cumulus bubbles showed that G was constant to an excellent degree of accuracy, both during the life of a single cloud tower and from tower to tower, regardless of location or external conditions. The mean value of G came out slightly greater than 0.2 $\sec^{-\frac{1}{2}}$, giving an E of about 50 ± 10 seconds. The highest penetrating bubble studied was a trade cumulus tower reaching 16,000 ft which did not, however, become glaciated.

b. *The life cycles of the individual towers observed.*—The cloud towers in the present study not only reached great heights, but penetrated tremendously high wind shears and definitely contained ice crystals throughout a significant portion of their life histories. It should be of considerable importance to determine whether equation (5) and the constant value of E obtained for the bubbles studied previously give here also a consistent relation between velocity, acceleration, buoyancy, and time. If so, it will be of interest to see how the present observations may be interpreted and clarified by means of this model. Most of the present towers have the advantage of being well isolated from interference with one another due to great wind shear and thus form an especially valuable test case.

To make this test, the original motion picture film was projected on a microfilm viewer, from which the heights of the bubble tops were read off at every frame (3.6 sec). Although the vertical resolution was still smaller than desirable, there being commonly only about 1 cm height difference between the emergence of a bubble and its death as an entity, the results of drawing a smooth curve through the points were extremely satisfactory. The measurements and method of calculation of velocities and accelerations for one of the strongest towers (called X on Figures 3 and 4) are shown in Figure 8. A dual criterion was used for picking the time of complete erosion, when $(-t)$ was to be set equal to zero. This time was chosen when the levelling off of the ascent was indicated on the graph, coincident with the loss of the rounded upper surface showing itself on the film. This transition is readily identified since the hard upper edges rapidly become fuzzy and diffuse when the spherical shape is lost. In applying and testing equation (5) on Tower X, therefore, the quantities w, $\dot{w}$, and $-t$ were taken from the curves shown in Figure 8. It was then desired to see whether reasonable and observationally supportable values of gB, the bubble's buoyancy, could give rise to values of G which both remained nearly constant throughout the bubble's life and averaged about 0.2 sec$^{-\frac{1}{2}}$ as established for the smaller cloud towers. When the values of the buoyancy are chosen with the aid of the sounding in Figure 6, under assumptions to be described presently, the resulting calculations of G are obtained which are shown in Table I. Under these conditions the average G, or $\bar{G}$, is 0.195 sec$^{-\frac{1}{2}}$ and the percentage spread in G, called Δ, is only 25 %.

The values of buoyancy in the column marked gB in Table I may be obtained for this bubble from the sounding in Figure 6 under several assumptions, the most crucial being that the San Juan radiosonde observation is applicable to the clear-air environment of the clouds. This is readily established by projecting the trajectory of the air surrounding the clouds at the appropriate heights (9.4—14 km) backwards in time to the time of the radiosonde. It is thereby shown that the air in the cloud locality at the middle of the photographic run was 100 miles due north of San Juan at the time of the radiosonde. If we consider, for example, the weak stable layer occurring between 10 and 11 km (which coincides with the layer of high wind shear) we see that it would have to have a north-south slope of 1/150, or that common for a middle-latitude front, in order to occur at a 10 % different elevation 100 miles to the north. In the trade-wind region, a north-south slope this great is out of the question. It is thus concluded that the observations on the sounding curve apply to the air in the cloud region with less than a ±10 % shift in height. Local time changes within the air mass are certainly smaller still. The second assumption in obtaining gB is that the ascent curve of the bubble forming Tower X is very closely given by the dashed (right-hand) moist adiabat on Figure 6, which originates from the environment sounding at cloud-base level. That this curve delineates the maximum possible buoyancy for this tower is supported by other work on oceanic trade cumuli (Malkus, 1954) showing that the cloud buoyancies at cloud-base level rarely exceed that contributed by water vapor alone. It will be noted that this adiabat recrosses the sounding curve just above 12.5 km, leaving the bubble some buoyancy at its demise at 12.24 km. Thus this adiabat, according to the bubble model, also represents near minimum buoyancy for the tower since isolated bubbles cannot continue to rise without positive buoyancy. In proceeding from the virtual temperature differences between the dashed adiabat and the sounding curve to the values of gB presented in Table I, a negative correction to the buoyancy due to the presence of suspended hydrometeors has been introduced. This correction allows for about 4.5 gm/m^3 of water or ice particles at 10.42 km, diminishing to 2 gm/m^3 at the bubble's demise at 12.24 km. This correction amounts to nearly 30 % of the total buoyancy and is both uncertain and arbitrary: it is simply

Table I. Tower X, April 1, 1953. Height range studied 10.42—12.24 km

Observation number	$-t$ sec	$(-t)^{\frac{1}{2}}$ sec$^{\frac{1}{2}}$	w mps	$\dot{w}$ cm/sec^2	gB cm/sec^2	G sec$^{-\frac{1}{2}}$
1	288	17.0	11.7	—2.2	14.0	0.22
2	270	16.5	11.2	—2.2	13.3	0.21
3	252	15.9	10.5	—2.2	12.7	0.21
4*	234	15.3	9.8	—2.2	11.5	0.20
5	216	14.7	9.2	—2.2	10.4	0.18
6	198	14.1	8.3	—2.8	9.0	0.18
7	180	13.5	7.2	—2.8	8.8	0.19
8	162	12.8	6.4	—3.0	8.6	0.20
9	144	12.0	5.8	—3.0	8.4	0.20
10	126	11.2	5.5	—2.2	8.2	0.19
11	108	10.4	5.3	—2.2	8.0	0.18
12	90	9.5	4.7	—3.0	7.8	0.19
13	72	8.4	4.4	—3.0	7.6	0.17
14	54	7.4	3.9	—3.8	7.6	0.18
15	36	6.0	3.0	—4.8	7.6	0.19
16	18	4.2	2.0	—6.2	7.6	0.22

*Bubble diameter measured as 1.33 km.

$\bar{G} = 0.195$
$\Delta = 25$ %

delimited by that reduction in buoyancy necessary to proceed from the dashed adiabat to the values of gB in the table which produce values of G consistent with those of the previous study. That these figures are not unreasonable, however, may be seen as follows: if all hydrometeors were being retained in the bubbles from cloud base upward, the water or ice content at 10.5 km would be about 18 gm/m^3. These clouds were, however, observed to be precipitating heavily from their bases. Thus a hydrometeor content from 10—25 % of this figure is plausible, especially when it falls within the range of observed water contents in large cumuli. The latent heat of freezing has been ignored in the present computation, the assumption being that most of the freezing took place below 10.42 km where the bubbles began to be tracked.

The other vigorous tower produced by this cloud (called Tower Y and denoted by the horizontal line in Figure 3) was also studied. It should be pointed out that Tower Y was composed of several bubbles, which accounts for its great width. Each of these was about the size of the single bubble composing Tower X and in Figure 3a four are plainly visible. The bubble studied is the right-hand one which ascended first. Its maximum rate of rise was the same as that of Tower X, namely 11.7 mps. The buoyancy for Y was also obtained from the dashed adiabat in Figure 6, with the same magnitude correction for the weight of suspended hydrometeors. $\overline{G}$ came out 0.18 sec$^{-\frac{1}{2}}$ with a percentage spread, Δ, of 45 %. It is believed that the presence of the neighboring bubbles disturbed the constancy of G, especially during the later portions of its life cycle. This was due to overly large ascent speeds acquired by this bubble's being pushed up by successors, resulting in too low values of G.

Next, one of the weaker towers was studied in the same manner and the results are presented in Table II. This is the bubble called Q, which was denoted by the inverted triangles in Figure 3. The significant feature of Table II is that a considerably lower buoyancy had to be chosen for this bubble to give the same value of $\overline{G}$ as the others. The buoyancy for this bubble was taken from the moist adiabat shown by the dotted line (left-hand adiabat) on Figure 6, with a correction for weight of hydrometeors of 3 gm/m^3 at 9.72 km diminishing to 2 gm/m^3 at its maximum height of 10.94 km. The resulting values of gB given in Table II average 0.55 times the values used for X and Y in the height range 10.42—10.94 km. This latter bubble (Q) possessed lower ascent rates and perished sooner than the preceding two described. It can now be seen that it must have been a considerably more dilute bubble, its level of origin being perhaps about 5.9 km or 19,300 ft rather than cloud base. It presumably formed from smaller bubbles and dilute wake material near this level, while the other two formed near cloud base. Its concomitantly smaller required temperature excess (about 1.3° C compared to about 2.6° C for X and Y) over the surroundings at 5.9 km is consistent with this point of view.

Table II. Tower Q, April 1, 1953. Height range studied 9.72—10.94 km

Observation number	$-t$ sec	$(-t)^{\frac{1}{2}}$ sec$^{\frac{1}{2}}$	w mps	$\dot{w}$ cm/sec^2	gB cm/sec^2	G sec$^{-\frac{1}{2}}$
1*	216	14.7	8.9	0	13.0	0.21
2	198	14.0	8.6	—0.9	12.5	0.21
3	180	13.4	8.4	—1.2	12.0	0.20
4	152	12.3	8.1	—1.6	11.1	0.18
5	144	12.0	7.2	—1.9	10.5	0.19
6	126	11.2	6.4	—2.2	9.8	0.19
7	108	10.4	5.9	—2.8	9.2	0.19
8	90	9.5	5.5	—3.1	8.8	0.18
9	72	8.5	5.1	—3.7	8.4	0.17
10	54	7.4	4.1	—4.3	8.0	0.18
11	36	6.0	3.0	—5.5	7.0	0.19
12	18	4.3	1.8	—6.2	6.0	0.20

* Diameter of bubble measured as 1.3 km.

$\overline{G} = 0.191$

$\Delta = 21$ %

It will be seen by inspection of Figures 3 and 4 that Tower Q rose on the extreme left side of Cloud I (upwind and upshear). In fact at the time it formed, this part of the cloud was almost entirely separate from the larger cloud mass to the right. The average width of the smaller cloud mass was only about 4 km, while Tower Y rose from a cloud mass at least 9 km in width. By the time Tower X rose from the left-hand portion of cloud, this section had grown until it, too, had attained an average width of about 9 km. These data might thus suggest that, under given conditions, a minimum horizontal cloud dimension is required to permit emergent buoyant elements to rise all the way from cloud base without dilution. Since the undiluted elements will, in general, compose the strongest and most penetrating towers, it may well be that for cumulus to attain a sufficient vertical thickness to give rise to precipitation, a comparable horizontal size must first be attained.

To investigate these points further, the other weak towers put up by Cloud I were studied. There were three such towers detectable on the film. One (P) was too feeble and short-lived to be treated quantitatively. One of the two remaining, called C, appeared on Print 12 just as the bubble studied in Tower Y was closing its life cycle. Although it appeared from the same large cloud mass as did Y, its buoyancy was the same as that of the diluted tower, Q. It had an active lifetime of 185 sec, a maximum updraft speed of 7.2 mps, and a height range of 10.4—11.2 km.

The final tower was the very last one appearing on the film sequence, called *R*. In order to have the same value of *G* as the other towers, it had to be slightly dilute and to follow a moist adiabat about half-way between the dashed and the dotted curve on Figure 6. It covered a height range from 10.6—11.85 km, exhibited a maximum updraft speed of 7.8 mps, and a life period of 275 sec, just short of those of the strongest towers. At the time of its emergence, the entire cloud mass of Cloud I was apparently beginning to decay, and although the bubble came from the main portion of the cloud, the horizontal dimension of that body was then only a little over 7 km. Thus it is seen that although the strength of the emerging towers and the dimension of the producing cloud mass in general appear to be related, another factor or factors must also be operative, since the largest cloud mass produced weak as well as strong towers. A suggestion concerning one of these factors is made in later paragraphs.

The major features of the six towers put up by Cloud I are summarized in Table III. The towers are arranged in order of their appearance, the times shown being minutes elapsed since the beginning of the run. In the table, the measured diameter of each bubble (measured at the starred times in Tables I and II) is compared to the radius of curvature calculated from equation (4) using $E = 50$ sec. The earlier study by Malkus and Scorer showed, as Figure 7 suggests, that *D* as measured and *R* came out very nearly equal, indicating aperture angles, $2\,\Theta_m$, for cloudy bubbles of about 60°. The good agreement in the present cases gives further support to the applicability of the model. The basic assumption that the actual ascent velocity w only slightly exceeds the limiting velocity w_L is also supported. When the calculated *R* is used to obtain w_L from the combined equations (2) and (3), it is found that on the average w exceeded w_L by 6 % at the starred times.

The column marked $R_{\max}$ gives the approximate dimension of each bubble as it first emerged from the cloud top, calculated by extrapolation from equation (4). It will be noted that the strong, undilute towers, X and Y, had maximum radii in excess of 2 km, while the weaker ones just exceeded 1 km. There is a corresponding variation in the maximum ascent velocities at the time of

Table III. Summary of Towers Studied

Tower name condition	Print first appeared number	Time min since beginning of run	D [meas. at $(-t)^*$] km	$R = EgB(-t)^*$ km	$R_{\max}$ km	$W_{\max}$ mps	Cloud width km	Total lifetime sec
Y undilute	6	7.2	2.1	2.1	~ 2.2	11.7	9	318
C dilute........	12	14.4	0.96	0.85	~ 1	7.2	9	185
Q dilute........	23	27.6	1.3	1.4	~ 1.3	8.9	4	216
X undilute.....	34	40.6	1.33	1.35	~ 2.1	11.7	9	288
P..............	39	46.6	Too weak to study				9	
R slightly dilute	50	60	1.3	1.3	~ 1.3	7.8	7	275

emergence, given in the column marked $w_{\max}$.

Two of the four weaker towers emerged from smaller cloud masses while the other two emerged from the largest ($\sim$ 9 km) ones. In the case of the latter, namely C and P, one noteworthy feature is held in common. In each case, the weak tower followed its predecessor's emergence after an unusually short interval, 7.2 minutes in the case of C, and 6 minutes in the case of P. The strongest towers, Y and X, were separated by more than a half hour, while X and R were separated by nearly 20 minutes. If, as suggested by writers on the bubble model, the larger cloudy bubbles are formed by aggregation of smaller ones at low levels within the cloud, this fact becomes somewhat clarified. A certain time interval is apparently required for a sufficient number of small bubbles to accumulate in the low cloud levels in order to form a large vigorous one which can rise to emerge undiluted from cloud top.

It may be seen that each bubble once it emerged from protection by the main cloud body penetrated a vertical distance very nearly equal to its maximum radius at emergence. Furthermore, those bubbles which did not follow their predecessors too closely rose through a height within cloud (from their origin level to the top of the cloud body) very comparable to the width of the protecting cloud body. Similar conclusions were also deduced by Malkus and Scorer for the smaller cumulus towers. It appears that the presence of ice crystals has no noticeable effects upon the bubbles during their active lives, although it may be responsible for slower dissipation of their wakes and remnants.

The last column on the right shows that the very vigorous undilute bubbles had active lives of about 300 sec or five minutes (X could have been followed this long on the film) and successively weaker bubbles had successively shorter lives. Bubble P probably existed independently for 100 sec or less. As noted earlier, the remnants of the towers went on rising at $^1/_2 - 1$ mps for about 10 minutes after the round tops were lost, achieving heights greater than 13 km. Then dissipation set in and occupied another 10—15 minutes without much further ascent taking place.

Since the present discussion has in part concerned undiluted cloud elements, some rising all the way from cloud base moist adiabatically, it must be emphasized that any resemblance to the hypotheses and results of the parcel method is strictly superficial. The parcel method considers cloud elements which in no way interact with the surrounding air and which would continue to accelerate upward wherever the parcel density is less than that of the environment. In the present case, a rough calculation shows that parcels becoming saturated at cloud base would emerge from cloud top at 10 km with upward velocities well in excess of 60 mps and still increasing! Since the bubble, on the other hand, is hypothesized to be travelling at very nearly its limiting velocity at all times (at least after emergence) its interaction with the surroundings is held to be absolutely vital. In fact, the buoyancy force is just overbalanced by form drag (produced by flow around the bubble cap) and is not producing a resultant upward acceleration. On the contrary, the bubble's upward velocity is in general decreasing with time due to erosion, despite the fact that the buoyancy is positive. To summarize: the parcel method prescribes no relations between the velocity and radius of a convective element and an erroneous relation between velocity, buoyancy, and time. The present model suggests quantitative relations between these parameters, which are tested here.

c. *The horizontal motions of the towers and the effects of wind shear upon their life cycles.* — Figure 9 shows the San Juan radiowind observation for 1500 GCT. The small triangles, squares, and X's denote the horizontal speeds of several of the cloud towers at the heights plotted. These represent speeds in the plane of the photographs which, it will be remembered, fortunately coincided with the plane of the ambient wind. Each such symbol represents an average horizontal speed from one print to the next (1.2-minute interval). It proved too difficult to get 3.6-second horizontal speeds from the microfilm viewer as was done in the case of the vertical speeds. Nevertheless several deductions may be drawn from Figure 9. It is first of all encouraging to note that the cloud towers began to shear horizontally at the level at which the intense shear in the ambient wind set in ($\sim$ 9.7 km).

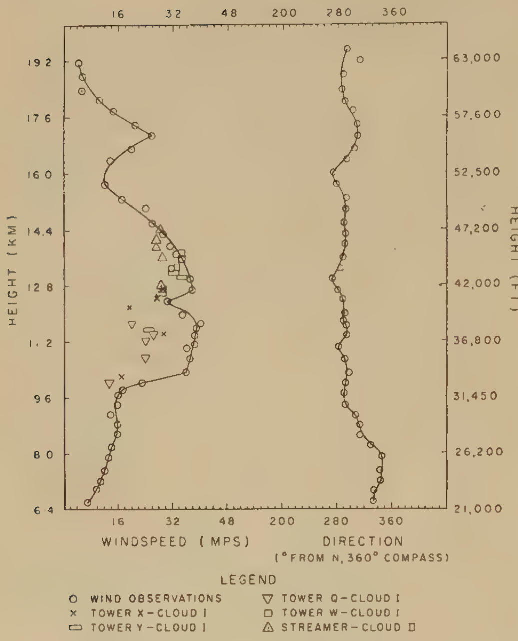

Fig. 9. The wind profile plotted from the San Juan radiowind observation for 1500 GCT, April 1, 1953. These points, marked by circles, were obtained upon reduction of the original data for this study. The curve on the left is wind speed in meters per second; that on the right is direction in degrees from true North. The layer of strong shear has been found on other soundings in the area, and on previous and subsequent soundings at San Juan. The other symbols, such as triangles, bars, squares, and X's are horizontal speeds of the various towers, as denoted on the figure.

This fact supports the validity of the height calculations from the films and the applicability of the sounding to the cloud region. Second, it is noted that above heights of about 12.5 km, where even the most vigorous bubbles ended their active life cycles (made a transition to much weaker ascent rates), the horizontal speeds of the towers draw close to (but never exceed) the outside windspeed.

More detailed consideration of the horizontal motions of the towers of Cloud I are possible, however. It was shown by Malkus and Scorer that in the case of a tower ascending through a shearing wind field equation (5) should be replaced by

$$\frac{3}{2}E^{-\frac{1}{2}} = G = \frac{(-t)^{\frac{1}{2}} gB(1-\dot{w}/gB)^{\frac{1}{2}}}{w(w^2+u^2)^{\frac{1}{2}}} \qquad (6)$$

where u is the horizontal velocity of the bubble relative to the air. This equation is readily derived by setting up a differential equation analogous to (1) for the horizontal motion of the tower (where drag forces only are operative) and writing an expression for the total vector drag force which depends now on (u^2+w^2). When the vertical component of this total drag force is substituted into (1), K is eliminated and (6) is obtained. It has been shown that in most shearing wind fields the difference between the results of (5) and (6) would be only about 2%, but when u is of the same size as w, use of (5) gives about a 20% overestimation of G. Figure 9 indicates that in the present case u is indeed comparable to w, since in the region of strong shear the horizontal tower velocities fall short of the wind velocity by 9—15 mps. However, it may also be shown that a rate of buoyancy decrease of the magnitude experienced by the present bubbles at these heights should lead to about a 15—20 % underestimation of G. Since these errors are compensatory, and since the present observations are probably not reliable to better than 15—20 % anyhow, no attempt will be made here to introduce such refinements.

The data in Figure 9 also provide a means for a direct test of the horizontal equation of motion for cloudy bubbles. Analogously to (1), this equation may be shown to be

$$\dot{u}_b = -\frac{u}{\sqrt{u^2+w^2}}K(u^2+w^2) \qquad (7)$$

where u_b is the component of the bubble's horizontal velocity along the axis determined by the external wind, u_E; u is the relative velocity between bubble and surroundings, namely $u = u_b - u_E$; and the dot indicates time differentiation. The constant K was shown to be the same as K in equation (3), namely $9/4R$. Subtracting $\dot{u}_E$ from both sides of (7), we have

$$\dot{u} = -wU' - \frac{u}{\sqrt{u^2+w^2}}K(u^2+w^2) \qquad (8)$$

since $\dot{u}_E = wU' = wdU/dz$ and $\dot{u} = \dot{u}_b - \dot{u}_E$, where U' or dU/dz is the external wind shear.

If the bubble has been rising through constant shear for several hundred meters and if it is still fairly near the beginning of its life cycle so that K is changing only slowly,

$\dot{u}$ is very small, as is $\dot{w}$, and (8) may be solved approximately to give

$$-\frac{u}{w} \cong \frac{4RU'}{9\sqrt{u^2+w^2}} \tag{9}$$

after substitution of (3) for K.

The region of strong shear on Figure 9 corresponds to the earlier phases of the cycles of the towers studied. Hence (9) may be tested. The figure shows that Tower X possessed a u of about —15 mps in this region and that for Tower Q, u averaged about -12 mps. Assuming that these bubbles had been rising through the shearing layer long enough for $\dot{u}$ to be very small, and taking the observed U' of 3×10^{-2} sec^{-1}, the radius of curvature R for Tower X comes out 1.8 km and R for Tower Q comes out 1.4 km from equation (9), compared to the calculated values of 2.1 and 1.3 km respectively which appeared in Table III. These independent results are consistent with the predictions of the model and agree within observational error, although it must be conceded that the measurements and the approximations made are such that this high degree of agreement is somewhat surprising.

It is not clear from the observations whether, as the bubble continues its life cycle, the horizontal drag coefficient increases in the same manner as its vertical counterpart, which the model declares that it should, although this is at least roughly suggested by the fact that $u = u_b - u_E$ seems to be decreasing in magnitude before evaporation sets in and makes it impossible to measure further. Changing wind shear coupled with the difficulty of tracing a single point in its horizontal travel precludes an accurate quantitative test of (8) solved for G (after substitution of $K = 9/4R$ and $R = EgB(-t)$ such as was done for the vertical equation (1).

In a shearing wind field a rising bubble should have a horizontal as well as a vertical component to its trailing turbulent wake. Earlier observations by Malkus (1949) suggest the presence of such a wake region in the horizontal, since several hundred feet of "dying cloud" were commonly found on the downshear edge of cumuli.

V. Conclusion

The clouds studied in this paper are of interest for two main reasons: first, they are the largest clouds in conditions of strongest shear to which the techniques described here have been applied. Previous clouds investigated by the Woods Hole group have been small or middle-sized trade cumulus and fair weather cumulus of middle latitudes, none of whose tops reached the freezing level. Some similarities and some contrasts between these clouds and the smaller ones studied earlier are striking. The outstanding similarity is the applicability of the same erosion constant, E, to the towers. The predominant contrast is the relatively less important role played by mixing with the clear-air environment in the bigger clouds. This is not to say that interaction between cloud elements and their surroundings is any less important, since it was demonstrated here that the strongest bubbles studied emerged from cloud top with velocities less than 1/6 that of a non-interacting parcel. In fact, it has been indicated that a minimum cloud dimension is necessary to shield the innermost core from dilution. In the case of these clouds, a mass roughly 9 km across (in the plane of the wind and the wind shear) could produce at intervals of about 20 minutes, undiluted bubbles 2 km in diameter which emerged from cloud top rising at 11 mps. The relation between radius, buoyancy, velocity, and lifetime of these elements agreed very satisfactorily with the relations prescribed by the model of eroding cloud towers.

The greatest importance meteorologically of the clouds studied is, however, their role in the over-all picture. It must be supposed that clouds of this type and scale, although rarely observed from the ground due to prevailing overcasts under disturbed conditions, are the rule and not the exception when an extended polar trough reaches down to trade-wind latitudes.

It is well established (RIEHL, 1950) that the strong and high-penetrating convective activity which occurs in these troughs is the means by which the upper troposphere receives the major fraction of its latent energy supply. A sample calculation will illustrate the magnitudes involved. Assume that at the 25,000 ft level, a single saturated cloud tower is active at a given moment in an area 30 km on a side (roughly correct for April 1, 1953). If the updraft speed is 10 mps and the draft is 2 km on a side, continuity will be met by subsidence at 4 cm/sec over the remaining area. Since even the more dilute towers at this elevation have about 3.0 gm/kg water vapor content and the ambient air from the sounding less than 0.5 gm/kg, the net upward transport of water vapor is probably not less than 6×10^7 gm/sec or 3.6×10^{10} cal/sec in latent heat. Distributed over the area involved, this is 400 cal/cm² per day. This figure should be compared to a several months' average evaporation rate of 250 cal/cm² per day calculated for a similar latitude in the Pacific tradewind region by Riehl, Yeh, Malkus, and La Seur (1951). Clouds such as these thus play a major role in maintenance of the energy budget of the trades and on that basis alone merit further study.

Acknowledgments

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BÖRTZELLS, ESSELTE, STHLM 55

Contribution No. 717

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A preliminary note on the time scale in North Atlantic circulation

L. V. Worthington*

Summary—Recent observations show that the temperature and salinity relationship of the North Atlantic Central Water Mass has changed significantly during the fifteen year period 1935-1950. This evidence, coupled with a reassessment of certain budgeting problems which arise from the exclusive use of the circulation theorem, points to a rapid turnover of water from the surface to mid-depths. It is shown that the North Atlantic Deep Water has suffered a loss of oxygen in the last twenty years; from this it is surmised that the bulk of this water was formed during the period of catastrophic cold from 1810 to 1820.

A question of great importance to the understanding of the circulation of the oceans is that of how long a period has passed since a given water type has been in contact with the atmosphere. It has long been generally accepted that the cold water which fills the deeper portions of the ocean basins has been cooled by contact with the atmosphere in high latitudes.

In the North Atlantic, Iselin (1939) has shown that a temperature-salinity curve (through the range 18° – 36·5‰ to 8° – 35·1‰) can be constructed from surface observations in late winter, along a North-South band in mid-Atlantic which differs only slightly from the temperature-salinity curve usually obtained from vertical observations (hydrographic stations) in large areas of that ocean. This led to the concept that this water mass is formed by contact with the atmosphere and that lateral mixing and large scale sinking of surface water along σ_t surfaces are responsible for maintaining the consistent T/S relationship.

While it is by no means clear how such sinking apparently continues through the summer months there are indications, apart from the consistency of the surface and subsurface Temperature-Salinity relationship, of the existence of such a mode of circulation. There is no serious doubt, for example, that the Gulf Stream System transports a large volume of water northwards across the 45th parallel, but if we are to believe solely in geostrophic circulation little of this water is returned to the south. It is possible to arrive at a rough estimate of the amount of water involved by computing the net northward volume transport between two stations, one on either side of the ocean, according to the geostrophic equation.

For purposes of this inquiry two composite stations were constructed from Wüst and Defant's (1936) subsurface atlas of temperature and salinity, one at 46°N, 45°W close to Flemish Cap and one at 48°N, 10°W on the European continental slope off d'Ouessant. The northward volume transport (relative to the 2,000 decibar surface) between these two stations was computed by means of the geostrophic equation and found to be 38 million m^3/sec. If the Labrador Current carries 5 million m^3/sec. southward, to the west of a line drawn between the two stations there remain 30 million m^3/sec., or thereabouts, which the geostrophic equation

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is unable to account for since the pressure gradients below the 2,000 m level are so small as to be negligible.

Evidently this large amount of water disappears north of these stations as far as geostrophic circulation is concerned, and it is perhaps significant that roughly the same amount of water reappears in the Gulf Stream System as far as geostrophic circulation is concerned, between the Straits of Florida and Cape Hatteras. Many sources including WÜST (1924) and PARR (1937) agree that the volume transport of the Florida Current in the Straits (subject to short period variations) is about 25 million m^3/sec., and frequent sections from Montauk Point to Bermuda (ISELIN, 1940) have shown that there the volume transport of the Gulf Stream is about 72 million m^3/sec. If the Antilles Current adds 15 million m^3/sec. to the Florida Current north of the straits there remain 32 million m^3/sec. which must be added to the current by non-geostrophic means, presumably by horizontal flow along σ_t surfaces.

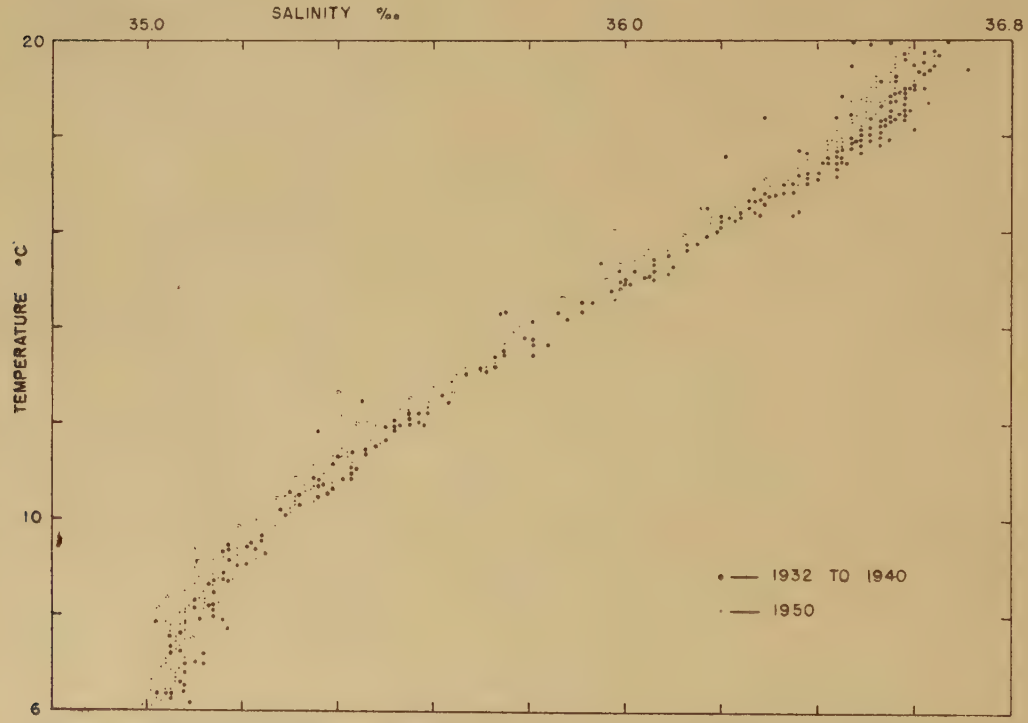


Fig. 1. Comparison between the temperature-salinity relationship of Gulf Stream Water in the years 1931-1940, and 1950.

In attempting to assign a time scale to this movement it must be admitted that only the crudest estimates can be made on the basis of existing data. While it is contended that the water types which join the Gulf Stream in this region were once at the surface and that they submerged in high latitudes, little is known of the path by which they returned to lower latitudes. In the Florida Current region an average figure can be given of the rate of westerly flow, across a line drawn between the Little Bahama Bank and a point 100 miles off Cape Hatteras, which must take place in order to add

30 million m^3/sec. to the current; this average figure is about 3 cm/sec., or 1·5 miles per day or 550 miles per year. It seems likely that this is a maximum figure for speed of flow of this type because here the width of flow is narrowest. The minimum distance from the region of surface convergence for, let us say, the 10° isotherm is 3,000 miles, which at the maximum rate could be travelled in 5½ years.

While this rate of turnover is almost certainly too swift, changes have recently taken place in the characteristics of the Sargasso Sea which indicate that it is not absurdly swift. In Fig. 1 a comparison is shown between the Temperature-Salinity relationship in the Gulf Stream in the years 1932-1940 and in 1950. Most of the stations included fall on the Montauk Point-Bermuda section, some of the earlier (1932-1933) stations are on the Chesapeake-Bermuda section.

In order to give a quantitative measure of the amount of this change Table I was constructed, by means of the salinity anomaly method. ISELIN'S (1936, Figs. 25 and 53) temperature-salinity curves for the Sargasso Sea were taken as normal. The average departure from these curves was computed for both the 1932-1940 and the 1950 Gulf Stream observations in 2°C steps, as follows:

Table I

Temp. Range °C	*Sal. Anom.* ‰ 1932-1940	*No. of Obs.* 1932-1940	*Sal. Anom.* ‰ 1950	*No. of Obs.* 1950	*Amount of Change (Fresher)*
18 – 16	0	75	0·04	44	0·04
16 – 14	+ 0·01	34	0·03	26	0·04
14 – 12	0	36	0·03	23	0·03
12 – 10	0	33	0·03	35	0·03
10 – 8	0·02	32	0·04	35	0·02
8 – 6	+ 0·01	31	0·01	33	0·02
6 – 4	0	79	0·02	127	0·02
4 – 2	0	84	0·01	105	0·01

The irregularities which appear in the anomalies of both periods are thought to be real, and are ascribed to the impossibility of drawing a smooth temperature-salinity curve which is absolutely exact. The cause of this freshening (if it is indeed freshening; the same anomalies would appear if the water became about 0·2° warmer at the same salinity) is beyond the scope of this study. It is merely brought up to illustrate the fact that a change has occurred in a short time period, which argues for a brisk turnover from the surface to mid-depths, a turnover roughly consistent with the rate computed above from transport figures. That the anomalies diminish to barely significant proportions in the deep (4° to 2°) water can be taken to mean that the apparent freshening cannot be charged to differences in the technique of analysis or in the Standard Water.

In the North Atlantic Deep Water there is evidence in the form of oxygen measurements which points to a more recent turnover than is generally supposed to have occurred. SEIWELL (1934) presented contours of the dissolved oxygen content of the western North Atlantic at various levels. His deepest chart (2,500 m) of the distribution of dissolved oxygen in ml./l. is reproduced here as Fig. 2. It is based principally on *Atlantis* cruises from 1931-1933 and the *Dana* cruise of 1921-1922.

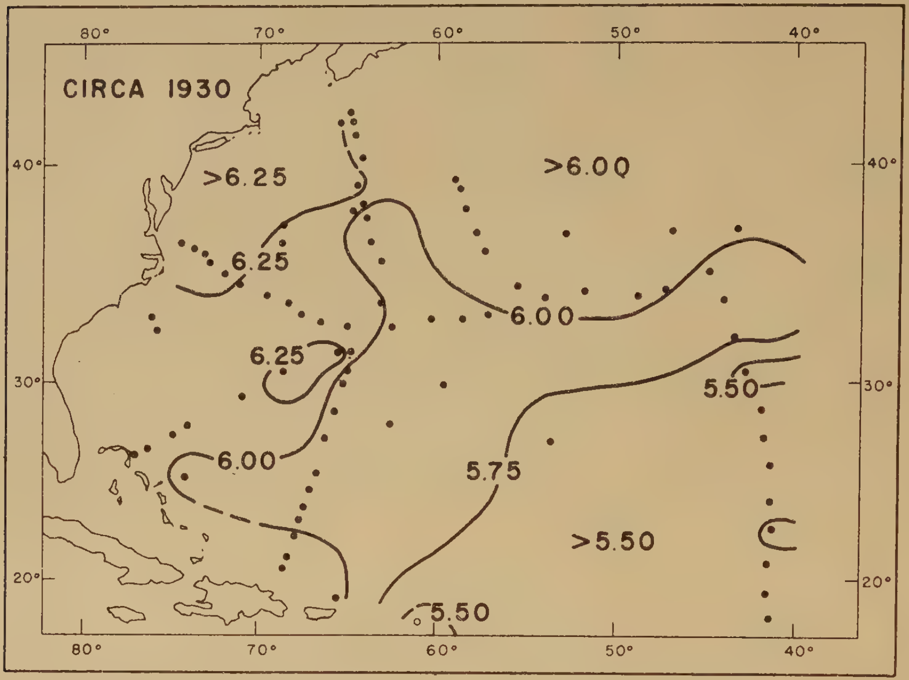
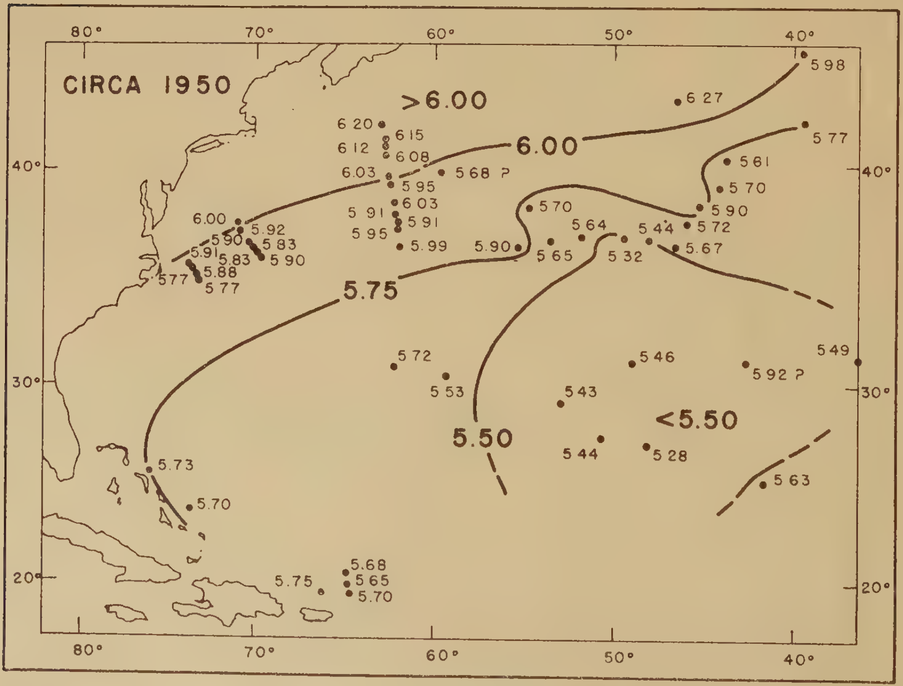

80°
70°
60°
50°
40°
CIRCA 1930
40°
>6.25
6.25
>6.00
6.00
6.25
30°
5.50
6.00
5.75
>5.50
20°
5.50
80°
70°
60°
50°
40°

Fig. 2. Distribution of dissolved oxygen, ml./l., at the 2,500 m level, from SEIWELL (1934).


80°
70°
60°
50°
40°
CIRCA 1950
>6.00
6 27
5 98
6 20
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6 12
6 08
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5 77
6.03
5 68 ?
5 61
5 95
40°
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6 03
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5 90
5.92
5 95
5 64
5 44
5 72
5.90
5 83
5.99
5.90
5 65
5 32
5.67
5.91
5.83
5 90
5.88
577
5 77
5.75
5 72
5 46
5 49
5 53
5 92 ?
30°
5 43
<5.50
5.50
5 44
5 28
5.73
5 63
5.70
5.68
20°
5.75
5 65
5.70
80°
70°
60°
50°
40°

Fig. 3. Distribution of dissolved oxygen, ml./l., at the 2,500 m level, from *Atlantis* stations, 1947-1954.

For comparison is offered Fig. 3, based on *Atlantis* cruises from 1947 to 1954, which shows an average over-all drop in dissolved oxygen at the same level of about 0·3 ml./l. In individual stations taken during both these periods there is little change in the oxygen content of the water column vertically between 2,000 m and 4,500 m, which cannot be ascribed to the inaccuracies in the method of determination. Below 4,500 m water of South Atlantic origin begins to be found. In Fig. 4 are plotted four oxygen curves from stations north of the Greater Antilles, two from 1954, one from 1932, and one from 1922, which illustrate the loss of oxygen in that area.

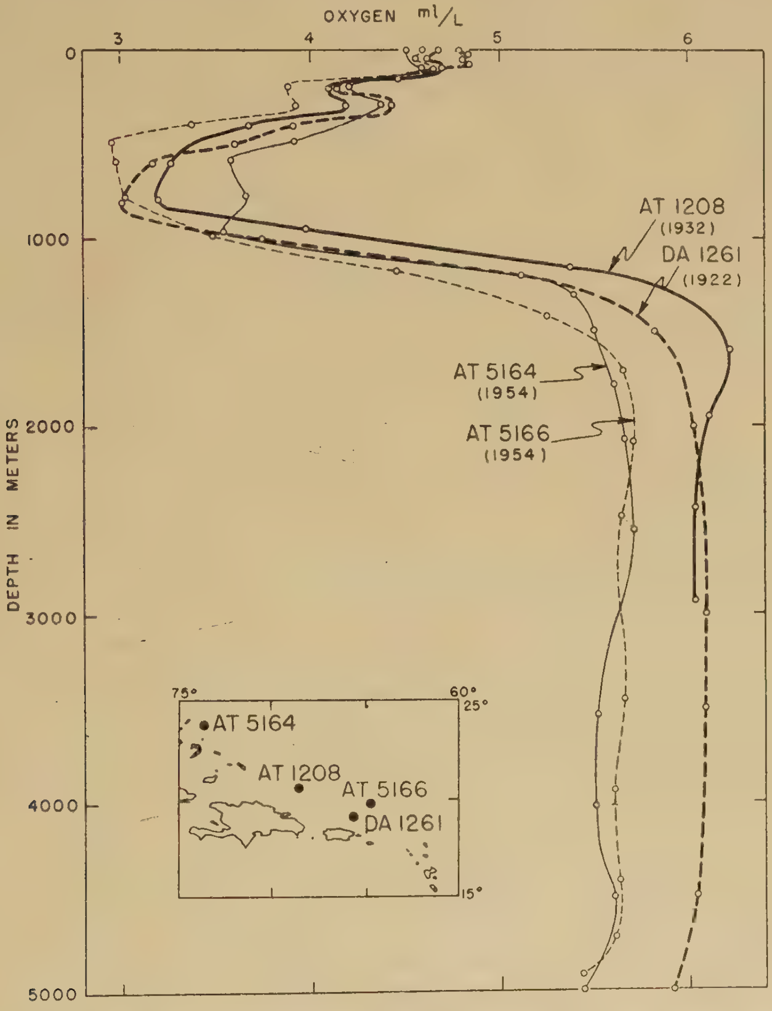

Fig. 4. Vertical oxygen curves illustrating the loss of oxygen in the North Atlantic Deep Water in the area north of the Greater Antilles.

Old and new data on the eastern side of the mid-Atlantic Ridge are not so plentiful, but they show that the deep water there has suffered a loss of oxygen comparable to that on the western side. In Fig. 5 are plotted the values of 0_2 in ml./l. at the 2,000 m level from the *Armauer Hansen* cruise of 1914 (GAARDER, 1927) and *Atlantis* stations made in the years 1947 and 1948. Unfortunately, the *Armauer Hansen* data do not extend to depths greater than 2,000 m and so often fall in the gradient between the oxygen minimum layer and the oxygen-rich deep water. However, the comparison serves to show that the oxygen attrition is not confined to the western basin.

The *Atlantis* Mediterranean cruise of 1947-1948 is of particular interest to this study because during this cruise deep oxygen data were obtained in both the eastern and the western basins of the North Atlantic and in the Mediterranean itself. In both the Atlantic basins considerably lower values of oxygen content were found in the deep water than in previous years, while in the Mediterranean Pollak (1951) was able to contour deep oxygen values from *Dana* (1928-1930), *Thor* (1908 and 1910) and *Atlantis* (1948) observations, as if synoptically. The oxygen titrations were; performed in the same manner throughout this cruise. These data infer that the loss of oxygen in the North Atlantic Deep Water is real, and cannot be attributed to differences in the technique of analysis.

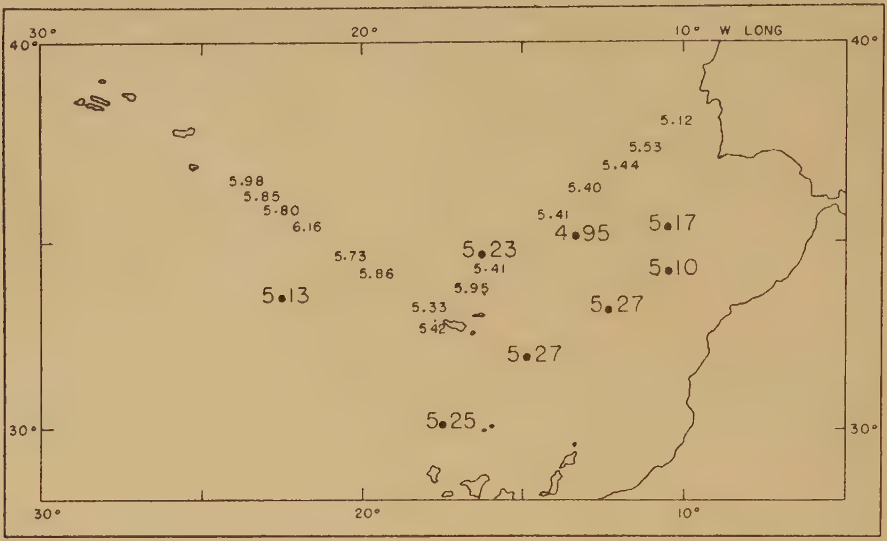

Fig. 5. Dissolved oxygen values, ml./l., at the 2,000 m level. Small figures are from the *Armauer Hansen* cruise of 1914 (Gaarder, 1927), the large figures are from *Atlantis* stations made in 1947-1948.

It appears from a comparison of Fig. 2 and 3 that in the western basin the loss of oxygen in the deep water has been roughly 0·3 ml./l. in twenty years, or 0.015 ml./l. per year. By assuming that this attrition has been going on at a steady rate it is possible to estimate by extrapolation the date at which this water was saturated with oxygen, presumably at the time that it was formed by atmospheric cooling. The date arrived at by this means is 1810.

The following sentences are quoted in this connection from Willett (1951): " At about 1800 there occurred a sharp reaction to lower temperatures which produced the severest cold on record in northern Europe, and coldness only slightly less severe in the northeastern United States. The famous ' year without a summer,' 1816, occurred during this period . . . " There exists a strong possibility that the bulk of North Atlantic Deep Water was produced during this catastrophe and that cooling in high latitudes in more recent years has not been sufficiently severe to produce enough water of high density to replace it.

These data are hard to reconcile with the age determinations made on sea water by KULP (1953) by means of radiocarbon 14. KULP's table of ocean water age measurements is reproduced here :

Table II

Location	*Depth, ft.*	*Depth, m*	*Apparent age, yrs.*
13° 35′N, 66° 35′W	surface	surface	recent
19° 24′N, 78° 33′W	surface	surface	recent
41° 00′N, 54° 35′W	surface	surface	recent
38° 42′N, 67° 54′W	13,500	4115	450 ± 150
63° 46′N, 00° 26′W	10,440	3182	500 ± 200
34° 56′N, 68° 14′W	16,560	5047	1,550 ± 300
35° 46′N, 69° 05′W	15,300	4663	1,950 ± 200
58° 19′N, 32° 57′W	6,000	1829	1,600 ± 130
53° 53′N, 21° 06′W	9,100	2774	1,900 ± 150

However, it appears from the positions and depths of KULP's measurements that all the subsurface samples in Table II were taken on or close to the bottom where conceivably some exchange of carbon between the sea water and the older bottom sediments or limestone rocks might have taken place. Age determinations of water from mid-depths should prove most interesting in this connection.

In summary, if the layer in contact with the ocean bottom can be put aside for the time being, we can consider (with some oversimplification) that there are two types of turnover which take place in the North Atlantic. The first, which is taking place continually, consists in water being transported to high latitudes by geostrophic and returned to lower latitudes by sinking along σ_t surfaces. In this type of circulation no violence is done to the water's identity as a water mass, and its temperature and salinity relationship remains essentially unchanged. Such changes as do occur are probably the result of the ocean's rapid response to climatic changes, and should take a prominent part in the study of these changes.

In the second, a vast amount of water of a single or nearly single water type is formed in successive years of catastrophic cold at high latitudes. To perform this, many water types must be combined into one by large scale top to bottom mixing. The North Atlantic Deep Water which was seemingly formed in this manner has penetrated as far as 40° South and comprises about half of the entire contents of the North and South Atlantic Oceans. How much of this water was formed in the individual catastrophe of 1810-1820 is open to question, as is the possibility of tracing different portions of this water to climatic changes in the more recent or remote past. Such questions cannot be answered without repeated re-examinations of the oceans.

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Contribution No. 722

BREVIORA

Museum of Comparative Zoology

Cambridge, Mass. November 29, 1954 Number 40

SOME MOLLUSKS FROM THE CONTINENTAL SLOPE OF NORTHEASTERN NORTH AMERICA[1]

By Arthur H. Clarke, Jr.

The continental slope area of northeastern North America has always been a relatively unknown and unexplored region. Only meager information has been on record in regard to the kind and abundance of its fauna. More knowledge is desirable, not only for academic interest, but also that proper evaluation may be made with the ultimate aim of supplementing man's ever-increasing need for additional sources of food.

With these objects in mind, in 1952 and 1953 the Woods Hole Oceanographic Institution began a survey of the bottom fauna existing on the continental slope area. An eighty-three foot trawler, the *Cap'n Bill II* was equipped for the task, and bottom trawlings were made along the slope from a point east of Cape Charles, Virginia, to a point southeast of Nova Scotia in various depths ranging approximately from 100 to 700 fathoms. Otter trawls were used carrying one and one-half inch mesh at the cod end, and measuring thirty-five feet, fifty feet, and sixty-five feet initially across the mouth. The work was under the direction of Mr. W. C. Schroeder of the Woods Hole Oceanographic Institution, to whom we are indebted for the fine array of mollusks collected.

Mollusks were not the primary concern of the survey, and the large size of the mesh prevented retention of the smaller specimens, though many of the larger species were obtained. These were submitted to Dr. W. J. Clench, Curator of Mollusks at the Museum of Comparative Zoology to be added to the research collection.

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[1] Contribution No. 722 from the Woods Hole Oceanographic Institution.

After identification of the mollusks collected, a search of the literature was made so that the data gained from this survey could be compared with previous records. Two papers by A. E. Verrill (1884 and 1885) were found listing the bathymetric ranges of all of the then known western Atlantic species of marine mollusks found below 60 fathoms.

Verrill's records have apparently been generally overlooked by many of the more recent compilers of molluscan lists. His data, as obtained primarily from material gathered by the U.S. Fish Commission steamers *Fish Hawk* and *Albatross* from 1880 to 1884, indicate much more extensive bathymetric ranges for a great many species than have subsequently been given. W. H. Dall, in his "Preliminary Catalog . . ." (1889) omitted much of Verrill's data, and although Dall frankly stated that his catalog was incomplete, this oversight has been perpetuated by later writers. It is urged that future investigators refer to Verrill's most complete and excellent list as a supplement to modern lists.

In the following tabulation of species collected by the *Cap'n Bill II,* the minimum depth range indicated by the data is given. For instance, if a particular species was found at two stations where the depths of trawling ranged from 200 to 250 fathoms and from 300 to 350 fathoms respectively, the minimum range would be 250 to 300 fathoms. A distinction is also made between living and dead specimens, and bathymetric ranges are given for each, if not identical. For comparative purposes, the broadest bathymetric and geographic ranges indicated by the literature are also included, and information sources are cited. When geographic ranges are extended, these localities are defined in terms of miles from a position on land. When not extended, approximate location only is indicated.

By examination of the following list of 28 species, it will be seen that these new data have extended the previously recorded bathymetric ranges of seven species (marked *) and the geographic ranges of six species (marked †).

List of Mollusca Collected

YOLDIA THRACIAEFORMIS (Storer)*†

One large dead specimen at station 72. *Bathymetric range*: 400 fms. dead (this survey); 29-182 fms. dead (Verrill 1884).

Geographic range: 240 mi. east of Sandy Hook, New Jersey (this survey); Gulf of St. Lawrence to Massachusetts (Johnson 1934); West Greenland (Thorson 1951).

PECTEN VITREUS (Gmelin)

Three living and two dead specimens at station 110. Three living specimens at station 208. *Bathymetric range*: 250-320 fms. (this survey); 50-800 fms. (Dall 1889). *Geographic range*: Arctic Ocean (Dall 1889); off Newfoundland and Nova Scotia (Johnson 1934); south of Nova Scotia (this survey); off Martha's Vineyard (Johnson 1934); east of Sandy Hook, New Jersey (this survey); west Florida [Gulf of Mexico] (Dall 1889); Europe; Mediterranean Sea; Africa (all Verrill 1884); west Greenland (Thorson 1951).

ANOMIA ACULEATA Müller

Living specimens attached to shells and rocks at stations 14, 19, 38, 53, 110, 131, 173, and 195. *Bathymetric range*: 145-320 fms. (this survey); 4-640 fms. (Verrill 1884); 0-80 fms. (Dall 1889). *Geographic range*: Arctic Ocean to Cape Hatteras, North Carolina (Dall 1889); south of Nova Scotia to east of Cape Henlopen, Delaware (this survey); Europe (Dall 1889).

A very variable species. The normal imbricated or scaly surface sculpture is entirely lacking in many individuals and in some entire large lots of specimens.

ARCTICA ISLANDICA (Linné)

Three single valves at station 1. *Bathymetric range*: 33 fms. dead (this survey); 6-90 fms. (Johnson 1934). *Geographic range*: east of Montauk Point, Long Island, New York (this survey); Arctic Ocean to Cape Hatteras, North Carolina (Dall 1889).

ASTARTE SUBAEQUILATERA Sowerby

Three small living specimens at station 86. *Bathymetric range*: 230 fms. (this survey); 22-410 fms. (Johnson 1934). *Geographic range*: Labrador to Florida (Johnson 1934); south of Nova Scotia (this survey).

PANOMYA ARCTICA (Lamarck)†

One very large, apparently freshly dead specimen at station 38. *Bathymetric range*: 190 fms. dead (this survey); 20-506 fms.

dead: 300 fms. alive (both, Verrill 1884). *Geographic range*: Arctic Ocean to Georges Bank; circumpolar (both, Johnson 1934); 170 mi. east of Barnegat Bay, New Jersey (this survey).

The specimen cited measures as follows: length 109 mm., height 74 mm., width (valves together) 48 mm. A similar specimen, alive and nearly as large, was taken nearby by the *Caryn* in 1949 (39°57′N., 70°38′W.), thereby confirming the fact that the species exists alive in this area.

CALLIOSTOMA BAIRDI Verrill and Smith

One dead specimen at station 83. One living specimen at station 146. *Bathymetric range*: 87 fms. dead; 65 fms. alive (both this survey); 56-640 fms. dead; 64-192 fms. alive (both, Verrill 1884). *Geographic range*: south southeast of Nantucket (270 mi. east of Barnegat Bay, New Jersey); east of Cape Henlopen, New Jersey (both, this survey); south of Martha's Vineyard to Florida Keys (Johnson 1934); Caribbean Sea (Verrill 1889).

The living specimen is very beautiful. Patches of lavender are seen through the thin iridescent periostracum which appears golden between the spiral rows of tubercules on the upper whorls and golden peach on the lower whorls. The inner nacre of the aperture shines with iridescent pink and green. The circular operculum is multispiral, typical of the family.

SOLARIELLA OTTOI (Philippi)

One dead specimen at station 72. Three living specimens at station 211. *Bathymetric range*: 400 fms. dead; 600 fms. alive (both, this survey); 64-1555 fms. (Dall 1889). *Geographic range*: south of Martha's Vineyard and Georges Bank (Johnson 1934); east of Sandy Hook, New Jersey (this survey); New Jersey; Virginia (both, Dall 1889); Florida Keys; West Indies (both, Johnson 1934); St. Thomas, Virgin Islands (Dall 1889).

NATICA CLAUSA Broderip and Sowerby

One very large dead specimen (23 mm. long) at station 182. *Bathymetric range*: 280 fms. dead (this survey); 13-1255 fms. dead; 238-843 fms. alive (both, Verrill 1884); 16-1537 fms. (Johnson 1934). *Geographic range*: Arctic [Ocean] (Verrill 1884); Labrador to off North Carolina (Johnson 1934); southeast of Cape Sable, Nova Scotia (this survey); Europe (Verrill 1884); Arctic and Bering seas to San Diego, California; Japan (both, La Rocque 1953).

POLINICES HEROS (Say)

One dead specimen at station 144. *Bathymetric range*: 150 fms. dead (this survey); 0-238 fms. (Dall 1889). *Geographic range*: Gulf of St. Lawrence to North Carolina (Johnson 1934); east of Chincoteague Island, Virginia (this survey).

POLINICES TRISERIATA (Say)*

One very large, dead specimen (33 mm. long) at station 144. One dead specimen at station 200. *Bathymetric range*: 100-150 fms. dead (this survey); 0-63 fms. (Dall 1889). *Geographic range*: Labrador to Cape Hatteras (Dall 1889); south of Georges Bank to east of Chincoteague Island, Virginia (this survey).

CAPULUS UNGARICUS (Linné)

One small living specimen attached to *Pecten vitreus* at station 110. *Bathymetric range*: 320 fms. alive (this survey); 1-458 fms. (Johnson 1934). *Geographic range*: south southeast of Cape Sable, Nova Scotia (this survey); Greenland to Florida (Johnson 1934); Europe (La Rocque 1953).

APORRHAIS OCCIDENTALIS (Beck)*

Living specimens at stations 95 and 177. Dead specimens at stations 38, 83, 86, 95, 164, 176, 182, and 184. *Bathymetric range*: 340-360 fms. alive, 90-365 fms. dead (both, this survey); 115-349 fms. alive; 34½-1000 fms. dead (both, Verrill 1884). *Geographic range*: Gulf of St. Lawrence to off North Carolina (Johnson 1934); southeast of Nova Scotia to south of Nantucket (this survey); west Greenland (Thorson 1951).

BUCCINUM CILIATUM Bruguière

One small living specimen at station 184 (southeast of Cape Sable, Nova Scotia). *Bathymetric range*: 265 fms. alive (this survey); 26-471 fms. (Johnson 1934). *Geographic range*: Arctic [Ocean] (Verrill 1884); Labrador to Cape Cod, Massachusetts (Johnson 1934); southeast of Cape Sable, Nova Scotia (this survey); Europe (Verrill 1884).

NEPTUNEA DECEMCOSTATA (Say)*†

Living specimens at stations 88, 95, 110, 165, 173, 182, and 184. Dead specimens at stations 38, 72, 86, 104, 164, 187, and 195. *Bathymetric range*: 270-360 fms. alive; 225-660 fms. dead (both this survey); 41-86 fms. alive; 6-322 fms. dead (both, Verrill 1884). *Geographic range*: Circumboreal (La Rocque 1953); Nova Scotia to Massachusetts Bay and Georges Bank (Johnson 1934); southeast of Nova Scotia to 240 mi. east of Barnegat Bay, New Jersey (south of Nantucket) (this survey).

Great variation of form exists in this species. Some specimens are attenuated to the extent that the length is 2½ times the greatest width. Other specimens show a length of only 1½ times the width. Variation is also seen in degree of sculpture, length of aperture in relation to overall length, etc. The possibility of the existence of one or more clines will be investigated.

NEPTUNEA DESPECTA TORNATA (Gould)*†

One small, dead specimen at station 159. *Bathymetric range*: 690 fms. dead (this survey); 10-471 fms. (Johnson 1934). *Geographic range*: Gulf of St. Lawrence to off Martha's Vineyard (Johnson 1934); 120 mi. east of Atlantic City, New Jersey (this survey).

COLUS ISLANDICUS (Gmelin)

Dead specimens at stations 5, 22, 23, 29, 84, 144, 201, and 225. *Bathymetric range*: 85-415 fms. dead (this survey); 20-1650 fms. (Dall 1889). *Geographic range*: Labrador to Norway (Johnson 1934); Arctic Sea to South Carolina (Dall 1889), south of Georges Bank to east of Chincoteague Island, Virginia (this survey).

COLUS STIMPSONI STIMPSONI (Mörch)

Two living specimens at station 152. One dead specimen at station 201. *Bathymetric range*: 330 fms. alive; 85-87 fms. dead (both, this survey); 1-471 fms. (Johnson 1934). *Geographic range*: Arctic Sea to [Cape] Hatteras, [North Carolina] (Dall 1889); south of Georges Bank to east of Cape Henlopen, New Jersey (this survey).

COLUS PUBESCENS (Verrill)*

Living specimens at stations 10, 13, 17, 53, 72, 139, 182, and

184. Dead specimens at stations 8, 10, 14, 17, 19, 35, 49, 83, 95, 104, 114, 131, 132, 139, 144, 164, 173, 184, and 225. *Bathymetric range*: 130-400 fms. alive; 90-415 fms. dead (both, this survey); 18-179 fms. dead; 192-640 fms. alive (both, Verrill 1884). *Geographic range*: Gulf of St. Lawrence to North Carolina (Johnson 1934); Nova Scotia to South Carolina (Dall 1889); southeast of Nova Scotia to east of Chincoteague Island, Virginia (this survey).

PLEUROTOMELLA AGASSIZI Verrill and Smith†

One dead specimen at station 211. *Bathymetric range*: 600 fms. dead (this survey); 39-1309 fms. alive; 1608 fms. dead (both, Verrill 1884). *Geographic range*: 105 mi. southeast of Nantucket (this survey); south of Martha's Vineyard to the West Indies (Johnson 1934).

SCAPHANDER PUNCTOSTRIATUS (Mighels and Adams)

One living specimen at station 109 and one living specimen at station 189. *Bathymetric range*: 240-305 fms. alive (this survey); 46-1255 fms. alive; 1362-1467 fms. dead (both, Verrill 1884). *Geographic range*: Gulf of St. Lawrence to West Indies (Johnson 1934); southeast of Nova Scotia (this survey); Barbados; Norway (both, Dall 1889).

ROSSIA SUBLAEVIS Verrill

One living specimen at station 69. *Bathymetric range*: 490 fms. (this survey); 45-640 fms. (Johnson 1934). *Geographic range*: Newfoundland to 32°33′15″N. (Johnson 1934); south of Georges Bank (this survey).

ILLEX ILLECEBROSA (Lesueur)

Two living specimens at station 68 and one living specimen at station 74. *Bathymetric range*: 450 fms. (this survey); 0-1022 fms.; beaks 1091-1917 fms. (both, Verrill 1884). *Geographic range*: south of Georges Bank (this survey); Greenland to Cape Hatteras (Johnson 1934).

CHIROTEUTHIS LACERTOSA Verrill

One living specimen at each of the following stations: 68, 69, and 74. *Bathymetric range*: 490-500 fms. (this survey); 435-2369 fms. (Johnson 1934); arms, 2949 fms. (Verrill 1884).

Geographic range: south of Georges Bank (this survey); Nova Scotia to West Indies (Johnson 1934).

MASTIGOTEUTHIS AGASSIZII Verrill*

One living specimen at station 102. *Bathymetric range*: 600 fms. (this survey); 640-1050 fms. (Johnson 1934). *Geographic range*: Gulf of Maine to North Carolina (Johnson 1934); southeast of Nova Scotia (this survey).

ALLOPOSUS MOLLIS Verrill†

One living specimen at station 69 (south of Georges Bank) and one living specimen at station 90 (southeast of Nova Scotia). *Bathymetric range*: 330-490 fms. (this survey); 238-1346 fms.; fragment, 1735 fms. (both, Verrill 1884). *Geographic range*: 110 mi. southeast of Cape Sable, Nova Scotia; south of Georges Bank (both, this survey); Nantucket to Chesapeake Bay, eastern Atlantic (both, Johnson 1934).

BATHYPOLYPUS ARCTICUS (Prösch)

One living specimen at station 69 and one living specimen at station 72. *Bathymetric range*: 450-490 fms. (this survey); 28-843 fms. (Johnson 1934). *Geographic range*: south of Georges Bank (this survey); Bay of Fundy to 32°N. (Johnson 1934).

GRANELEDONE VERRUCOSA (Verrill)

One living specimen at station 69. *Bathymetric range*: 490 fms. (this survey); 466-1255 fms. (Johnson 1934). *Geographic range*: south of Georges Bank (this survey); Nova Scotia to Delaware Bay (Johnson 1934).

Location and Depth of Stations Cited

Station Number	North Latitude	West Longitude	Depth in Fathoms
1	40°50′	71°09′	33
5	39°35′	71°57′	240-260
8	39°36′	71°52′	405-410
10	39°46′	71°35′	395-405
13	39°55′	71°27′	180-190
14	39°56′	71°26′	150
17	39°55′	71°17′	290-330
19	39°57′	71°13′	175-180
22	39°53′	70°53′	300-330

23	39°52′	70°51′	375-420
29	39°52′	70°43′	415-440
35	40°02′	70°24′	105-110
38	40°04′	70°12′	190-225
49	39°57′	69°37′	415-560
53	39°55′	69°26′	165-180
68	40°08′	68°19′	400-510
69	40°10′	68°16′	490
72	40°12′	68°08′	400-450
74	40°17′	67°53′	450-500
83	39°59′	69°32′	87-90
84	39°59′	69°35′	82-85
86	42°23′	64°58′	230-245
88	42°46′	63°22′	340-350
90	42°41′	63°33′	300-330
95	42°45′	63°47′	330-340
102	42°35′	64°03′	560-600
104	42°40′	64°08′	350-380
109	42°20′	65°03′	305-320
110	42°17′	65°06′	320-360
114	40°46′	66°40′	290-300
131	38°13′	73°40′	145-160
132	38°08′	73°45′	205-275
139	37°38′	74°14′	120-130
144	37°45′	74°09′	150
146	38°33′	73°18′	63-65
152	38°39′	73°05′	330-400
159	39°26′	72°10′	690-720
164	42°43′	63°50′	310-335
165	42°42′	63°47′	360-370
173	42°40′	64°10′	240-270
176	42°33′	64°17′	280-320
177	42°32′	64°19′	360-420
182	42°28′	64°31′	280-305
184	42°23′	64°52′	265-295
187	42°15′	64°58′	660-705
189	42°18′	65°05′	220-240
195	40°34′	67°02′	290-300
200	40°46′	66°48′	100-105
201	40°45′	66°51′	85-87
208	40°09′	68°24′	250-340
211	40°00′	68°49′	600-670
225	39°53′	70°40′	345-355

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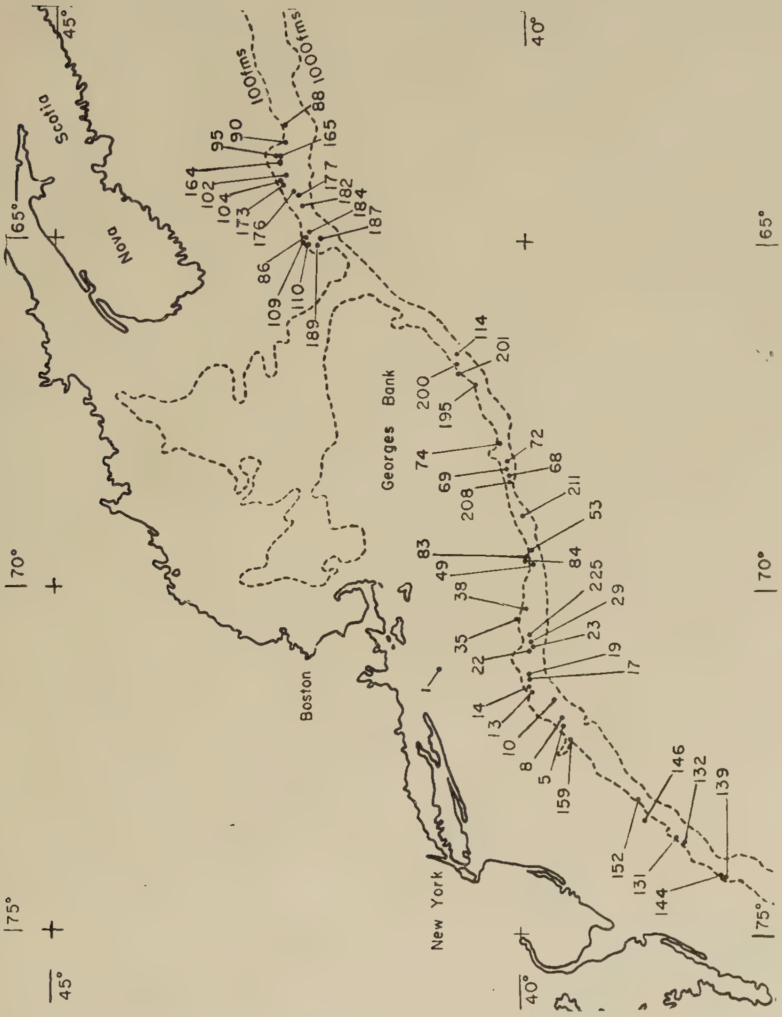
45°
Scotia
Nova
65°
100fms
1000fms
40°
70°
75°
Georges Bank
Boston
New York
88
165
90
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Map of continental slope area showing location of listed stations.

Contribution No. 723

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FRONTOGENESIS AND FRONTOLYSIS AS A THREE-DIMENSIONAL PROCESS

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FRONTOGENESIS AND FRONTOLYSIS AS A THREE-DIMENSIONAL PROCESS

By C. W. Newton

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(Manuscript received 12 May 1954)

ABSTRACT

A detailed analysis is presented to show the atmospheric structure during the earlier formative stages of a deep, upper trough. Over the western United States, a well-marked west-east frontal layer extends through the whole troposphere; in upper levels, this disappears within a short distance eastward. Individual changes in vorticity, vertical shear, horizontal temperature gradient, and vertical stability are discussed for air particles streaming eastward, out of the frontal layer. Factors in individual frontolysis vary in relative importance at different levels. In particular, variations of the vertical and horizontal components of vorticity and potential temperature gradient are chiefly effected, in the middle troposphere, by horizontal gradients of vertical motion and vertical gradients of the non-geostrophic wind component normal to the frontal layer. Near the maximum-wind level and near the earth's surface, divergence processes and deformation fields in the horizontal flow are of predominant importance. A general scheme is suggested for the vertical and transverse motions during frontolysis (or frontogenesis), in which the varying processes leading to changes in wind and temperature fields at different levels are interrelated in a three-dimensionally consistent manner.

1. Introduction

Despite the prominent role of the jet stream and the related high-tropospheric frontal zones (University of Chicago, 1947; Palmén, 1948) in recent meteorological thinking, the manner of formation of these phenomena is as yet unclear. The two principal theories of the jet stream approach the problem from different points of view. Rossby (1947) proposed that the wind field forms by processes involving lateral mixing of vorticity, and hypothesized that the solenoids adjust to the wind field by dynamic processes. Namias and Clapp (1949), on the other hand, proposed a kinematical concentration of the solenoid field, followed by a building up of the wind field. In the one case a thermally indirect, and in the other a direct solenoidal circulation, are postulated up until the time when equilibrium between wind and temperature fields is reached.

Because of the frequent association of high-level fronts with the jet stream, it is held (Palmén, 1951) that "any theory for frontogenesis should also be a theory for the formation of an upper jet stream." A satisfactory theory must eventually be based upon a sound knowledge of the actual circulations, but certain components of the circulation are generally so small as to escape direct observation. Determination of the magnitude or even the sign of vertical motions by ordinary synoptic methods may in many cases be unreliable, since when winds are strong a small error in wind direction or speed may result in a large error in computed vertical velocity.

The atmospheric structure as shown by a cross section in one location may be very much different from that in another location near by; hence, it should be possible to draw some conclusions about the circulation by studying changes in structure along the direction of the flow. This approach is followed in the present article, in an attempt to determine the types of motion involved in the formation and dissolution of frontal layers. In the synoptic example presented, these circulations are discussed in the "delta" region, where in high levels the air flows out of a frontal layer. This region is of particular interest, because of its frequent synoptic relation with low-level frontogenesis and cyclogenesis.

The principal characteristics of a sloping transition layer which must be accounted for in discussing frontogenesis or frontolysis are the following: (a) pronounced horizontal temperature gradient, (b) marked vertical stability, (c) strong vertical wind shear, and (d) vorticity higher than that found in the contiguous air masses outside the frontal layer.

Although there may be some degree of unbalance between thermal and actual wind fields, in general there is fairly close agreement at any given time. It seems likely, therefore, that for the most part the changes of the wind and temperature fields in frontogenesis or frontolysis take place simultaneously and as a result of the same processes.

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[1] Contribution No. 723 from Woods Hole Oceanographic Institution.

[2] Present affiliation: University of Chicago.

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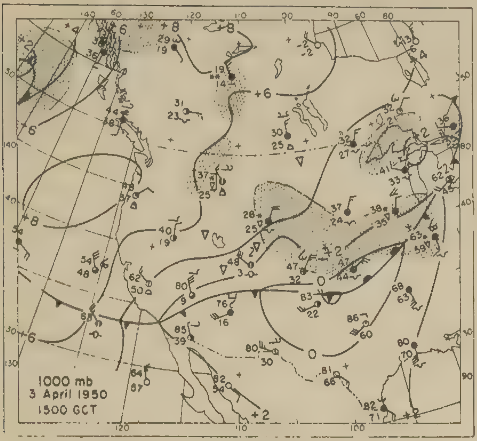

FIG. 1. 1000-mb chart, 1500 GCT 3 April 1950. Contour interval: 200 ft. Precipitation areas stippled.

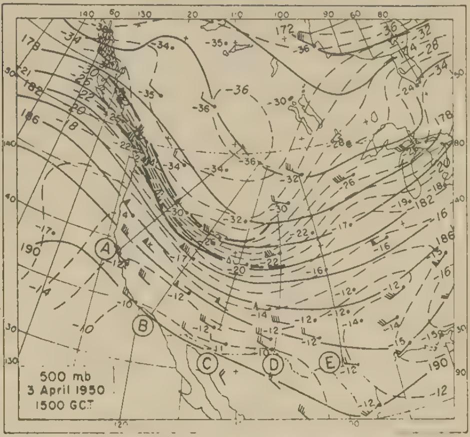

FIG. 3. 500-mb chart, 1500 GCT 3 April 1950. Light solid lines A to E indicate locations of cross-sections, figs. 5 to 9.

2. Structure of fronts on 3 April 1950

To illustrate typical variations in structure of frontal layers, a series of constant-pressure charts and cross sections is presented for 1500 GCT 3 April 1950.[4] At the surface (fig. 1), a distinct front extends ENE–WSW across the United States. At the 850-mb level (fig. 2), the thermal structure is quite complicated in appearance; the principal front, however, still remains distinct except over eastern Colorado, where the sounding at Denver indicates a very weak structure. Over the central plains states, the strong thermal concentration south of the main front represents the intersection of the 850-mb surface with the characteristic mT-air inversion, which at this time meets the ground over central Texas.

At 500 mb (fig. 3), the pronounced thermal concentration is still evident over the western United States, but further east the distinct frontal zone is absent. At 200 mb (fig. 4), the usual reversed temperature gradient is observed, the strongest contrast between the cold air to the south and the warm stratospheric air to the north being found approximately above the well-developed portion of the 500-mb front and weakening further east.

North of the meteorologically most active portion of the surface front (fig. 1), this front extends upward only to relatively low elevations; while over and west of the Rockies, where little or no frontal condensation phenomena are in evidence, the frontal layer is well developed through the whole depth of the troposphere.

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[4] For a description of the further development of this same case, the reader is referred to an article by Palmén and Newton (1951).

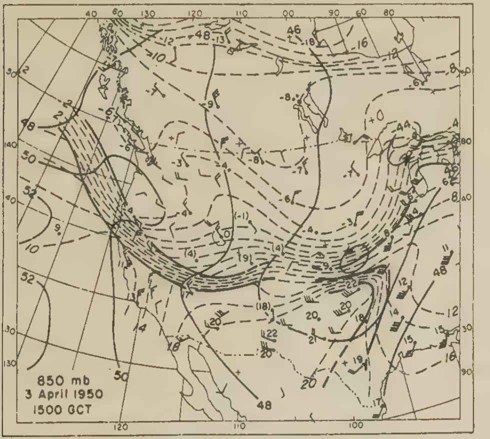

FIG. 2. 850-mb chart, 1500 GCT 3 April 1950. At stations, full wind barb-10 kn, triangle-50 kn (dashed for winds at somewhat lower level); temperature in deg C. Thin solid lines: contours (interval: 200 ft); dashed lines: isotherms (interval: 2C); heavy lines: frontal boundaries. Only south (upper) boundary of main front east of Rocky Mountains is shown, since lower boundary does not intersect 850-mb surface.

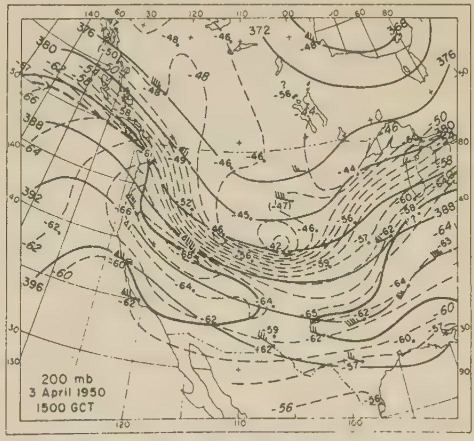

FIG. 4. 200-mb chart, 1500 GCT 3 April 1950. Heavy lines are tropopause intersections. Contour interval: 400 ft.

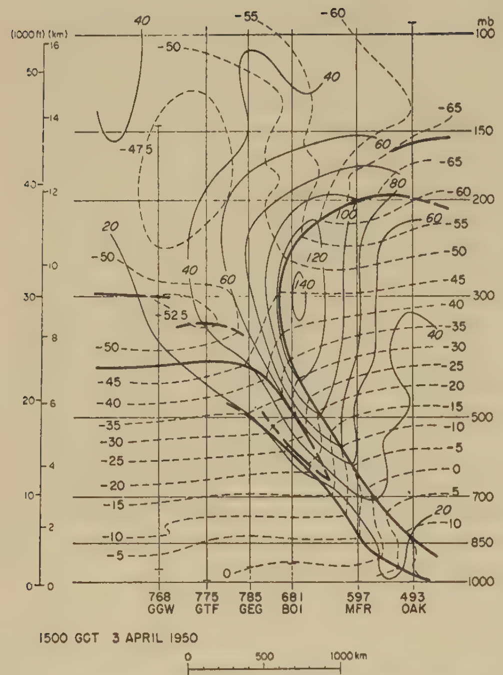

FIG. 5. Vertical cross-section along line A in fig. 3, 1500 GCT 3 April 1950. Heavy lines: frontal boundaries or tropopauses; thin solid lines: isotachs (kn); thin dashed lines: isotherms (deg C).

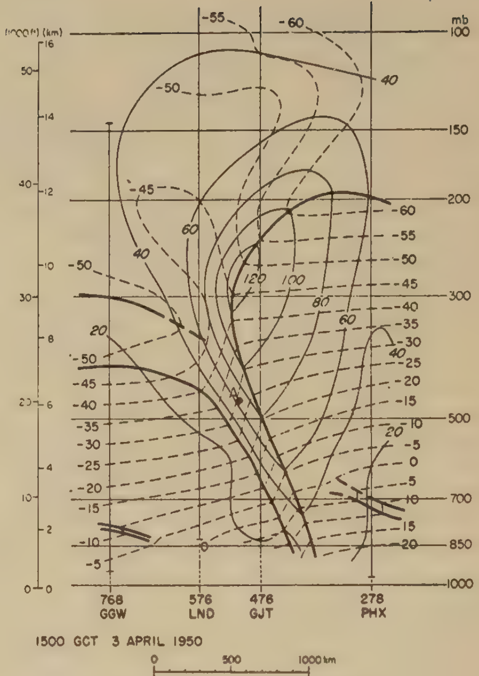

FIG. 7. Cross-section along line C in fig. 3, 1500 GCT 3 April 1950.

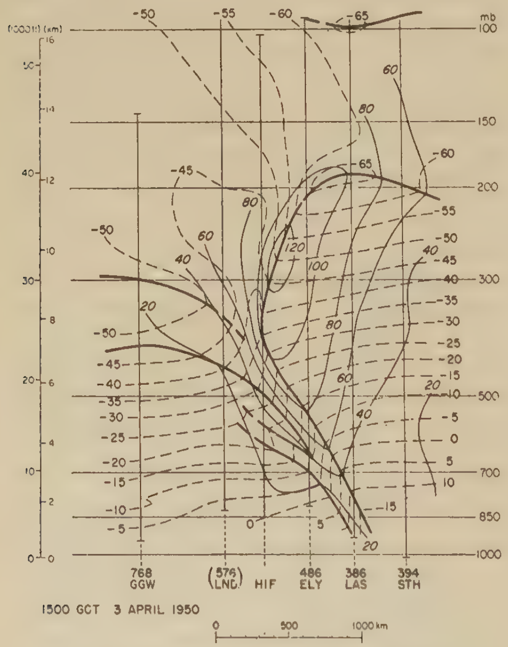

FIG. 6. Cross-section along line B in fig. 3, 1500 GCT 3 April 1950.

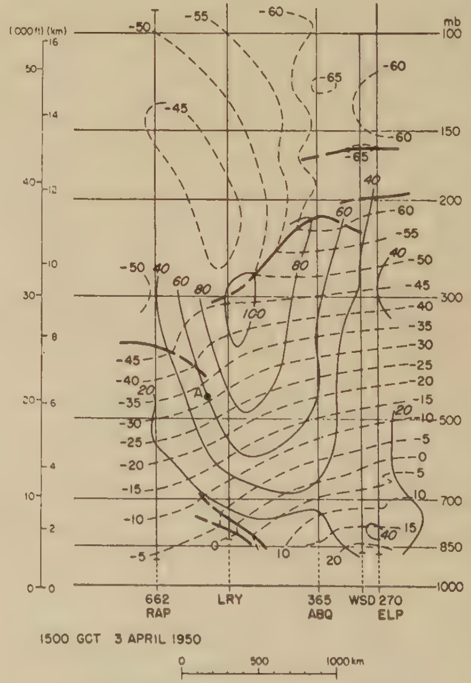

FIG. 8. Cross-section along line D in fig. 3, 1500 GCT 3 April 1950.

A more complete notion of the frontal structure is given by the cross sections shown in figs. 5 to 9, which are spaced at intervals of approximately 400–500 km (near the axis of maximum wind). The isotachs represent *total* gradient wind speeds, observed winds being used where available. In the lower levels (*e.g.*, fig. 5), the apparent disagreements between thermal gradients and vertical variations of wind speed result from the fact that the thermal wind is associated with directional changes and only partly with changes in speed; at 700 mb and above, the winds are in all cases nearly normal to the cross sections.

The three cross sections west of the Continental Divide (figs. 5 to 7) all show a distinct frontal layer extending up to the polar tropopause, the solenoidal field being perhaps best developed in fig. 5. Between figs. 7 and 8, a radical change in structure is observed, no evidence of a distinct frontal layer being found in the latter section. Further downstream (*e.g.*, fig. 9), the sections some distance east of the Rocky Mountains still fail to show a frontal layer in the higher troposphere. In the lower levels, below 600 to 650 mb, a well-developed front is again observed, overrun by the tropical-air inversion (*cf.* fig. 2). It was clear from the soundings and from historical continuity that the lower-level frontal layer in fig. 9 could not be identified with the higher-troposphere front further west, since it had formed independently at much lower potential temperatures (see section 5, below).

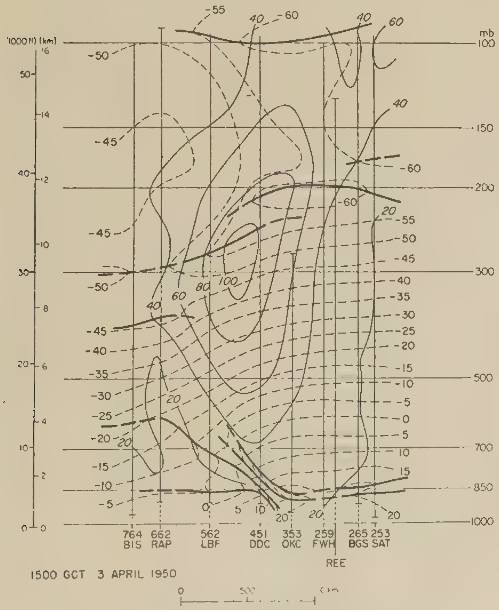

FIG. 9. Cross-section along line E in fig. 3, 1500 GCT 3 April 1950.

Palmén (1951) has already pointed out that in analogous situations (characteristic of the earlier stages of upper-trough development) the frontal layer is often very pronounced on the west side, though weak on the east side of a trough. The above example (and others that have been studied) suggests that, although slow variations in frontal strength are observed along the frontal layer, the actual breakdown of this layer into an indistinct solenoidal field occurs in a very short distance. Since the frontal region as a whole has a comparatively slow movement, rapid *individual* frontolysis (decrease of vertical and lateral temperature gradient, vorticity, and vertical shear) is undergone by the air streaming out of the frontal layer in the upper troposphere. Although (in the writer's experience) rapid formation of high-level frontal layers, such as observed in the very striking case presented by Reed and Sanders (1953), appears to be uncommon, individual frontogenesis and frontolysis of the character described above is frequently observed. The types of motion involved in actual formation of a previously non-existent frontal layer, and in individual frontogenesis, are presumably of similar character.

3. Equations for frontogenesis in wind and temperature fields

Individual changes in the horizontal and vertical potential-temperature gradients may be expressed (*cf.* Miller, 1948) by

$$\frac{d}{dt}\theta_y = \frac{\partial}{\partial y}\left(\frac{d\theta}{dt}\right) - \frac{\partial u}{\partial y}\theta_x - \frac{\partial v}{\partial y}\theta_y - \frac{\partial w}{\partial y}\theta_z, \qquad (1)$$

and

$$\frac{d}{dt}\theta_z = \frac{\partial}{\partial z}\left(\frac{d\theta}{dt}\right) - \frac{\partial u}{\partial z}\theta_x - \frac{\partial v}{\partial z}\theta_y - \frac{\partial w}{\partial z}\theta_z, \qquad (2)$$

where $\theta_x = \partial\theta/\partial x$, *etc.* Throughout this article, the x-axis is considered to lie along a streamline at the level under consideration (in the example shown, nearly parallel to the orientation of the front in upper levels), with the y-axis toward the left of the streamline.

In rapid frontogenesis or frontolysis, it is generally permissible to assume that the gradients of non-adiabatic temperature changes are small, though these may be important when condensation is involved. In (2), the sum of the two middle terms on the right is zero if the geostrophic assumption is made, and in such case stability changes are caused entirely by divergence and non-adiabatic processes. It would obviously be improper to make such an assumption here, since individual frontogenesis involves motion of air into changing pressure fields (confluence or difluence); hence, non-geostrophic motions must exist.

The complete equations for the components of vorticity about the z- and y-axes are

$$\frac{d}{dt}(f+\zeta) = -(f+\zeta)D_{xy} + \frac{\partial w}{\partial y}\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\frac{\partial v}{\partial z} + \frac{\partial \alpha}{\partial y}\frac{\partial p}{\partial x} - \frac{\partial \alpha}{\partial x}\frac{\partial p}{\partial y} + \frac{\partial}{\partial y}(ew) + F_{\zeta} \qquad (3)$$

and

$$\frac{d}{dt}(\eta - e\cos\gamma) = -(\eta - e\cos\gamma)D_{xz} + \frac{\partial v}{\partial z}\left(f - \frac{\partial u}{\partial y}\right) + \frac{\partial v}{\partial x}\frac{\partial w}{\partial y} + \frac{\partial}{\partial x}\left(\alpha\frac{\partial p}{\partial z}\right) - \frac{\partial}{\partial z}\left(\alpha\frac{\partial p}{\partial x}\right) + F_{\eta}, \qquad (4)$$

where $D_{xy} = \partial u/\partial x + \partial v/\partial y$, $D_{xz} = \partial u/\partial x + \partial w/\partial z$, $\zeta = \partial v/\partial x - \partial u/\partial y$, $\eta = \partial u/\partial z - \partial w/\partial x$, $e = 2\omega\cos\varphi$, γ is the angle between the x-axis and east, and the other symbols have their conventional meanings. The frictional torques F_{ζ} and F_{η} are of unknown, but probably small, magnitude. In (3), the third term on the right is not in general negligible, but in the present case has been evaluated to be an order of magnitude less than the preceding term, provided the x-axis is placed along the direction of the wind at a given level. The fourth and fifth terms (solenoidal) drop out if the vorticity in isobaric surfaces is considered,[5] while the next term is insignificant. In (4), the third term is four orders smaller than $d\eta/dt$, and the fourth term is zero under the hydrostatic approximation; but the next term ($= f\,\partial v_g/\partial z$, where v_g is the geostrophic v-component) cannot be neglected. Only important terms being retained, (4) becomes

$$\frac{d\sigma}{dt} = -\sigma D_{xz} + f\frac{\partial}{\partial z}(v - v_g) - \frac{\partial v}{\partial z}\frac{\partial u}{\partial y}, \qquad (5)$$

where $\sigma \equiv \partial u/\partial z$ closely approximates the total vorticity about the y-axis, since $\partial w/\partial x$ and e are insignificant compared with ordinary values of $\partial u/\partial z$. With the simplifying assumptions noted above, (1) to (3), and (5), may be grouped as follows with similar terms on the right-hand side in vertical order:

$$\frac{d\theta_y}{dt} = \qquad - \theta_y\frac{\partial v}{\partial y} - \theta_z\frac{\partial w}{\partial y} \qquad - \theta_x\frac{\partial u}{\partial y}, \qquad (6)$$

$$\frac{d\theta_z}{dt} = +\theta_z D_{xy} \qquad - \theta_y\frac{\partial v}{\partial z} - \theta_x\frac{\partial u}{\partial z} + \frac{\theta_z}{\rho}\frac{d\rho}{dt}, \qquad (7)$$

$$\frac{d\zeta_a}{dt} = -\zeta_a D_{xy} \qquad + \sigma\frac{\partial w}{\partial y}, \qquad (8)$$

and

$$\frac{d\sigma}{dt} = \qquad \sigma\frac{\partial v}{\partial y} \qquad + \zeta_s\frac{\partial v}{\partial z} - \theta_x\frac{g}{\theta} + \frac{\sigma}{\rho}\frac{d\rho}{dt}. \qquad (9)$$

Here $\zeta_a = (f+\zeta)$ is the absolute vorticity, and ζ_s refers to the "shearing vorticity" ($f - \partial u/\partial y$). Estimates of $d\rho/dt$ based on reasonable values of vertical motion indicate that, in (7) and (9), the last terms may be neglected in the following discussion.

In the present case, little reliability could be placed in vertical motions or non-geostrophic components determined by ordinary synoptic methods, so direct evaluation of the contributions of some terms on the right of the above equations was impossible. However, each of the vertically arranged terms in the first four columns contains a common unknown (D_{xy}, $\partial v/\partial y$, $\partial w/\partial y$ or $\partial v/\partial z$) with a coefficient whose approximate mean value can be determined, and the remaining terms can be estimated with fair accuracy from cross sections and constant-pressure charts. Hence, in principle this set of equations can be solved simultaneously.

4. Evaluation of factors in high-troposphere frontolysis

Constant-pressure charts and cross sections at 0300 GCT on 3 and 4 April 1950 showed that the high-troposphere frontal structure varied little during this period, except for a bodily displacement downstream. It seems legitimate, therefore, to evaluate the various terms in (6) to (9) by use of the structure observed at 1500 GCT 3 April 1950, with allowance for the downstream displacement.

Figs. 10 and 11 show the fields of potential temperature and shearing vorticity ($f - \partial u/\partial y$) corresponding to figs. 7 and 8. Considering both components of vorticity and of the potential temperature gradients, we note that on the whole the greatest change of these properties in the two sections is found in the upper middle troposphere. The following computations are performed for an element of air (indicated by point A on the cross sections) near the 450-mb level and at approximately 305K potential temperature, in the central part of the layer of strongest baroclinity. Within a reasonable range of estimates of the terminal position of the particle in fig. 11, the magnitudes of the quantities to be computed would not be seriously affected.

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[5] In that case, the vertical motion (w) must be referred to the height of an isobaric surface, which itself varies. For present purposes this is immaterial, since only gradients of vertical motion are discussed, and these are very much larger than the gradients of vertical motion of the isobaric surfaces.

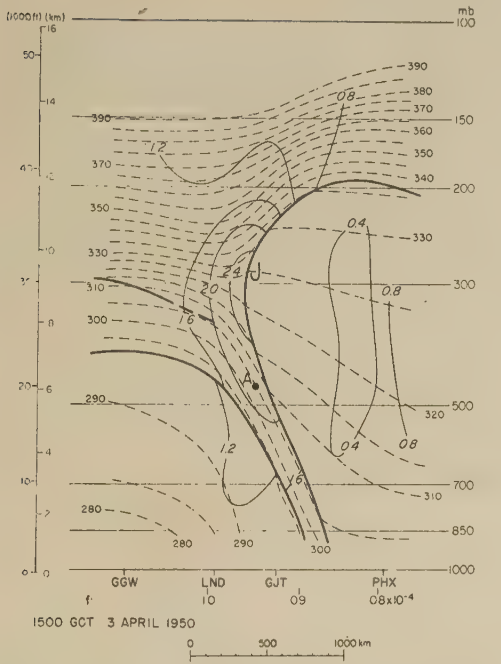

Fig. 10. Potential temperature (deg K, dashed lines) and shearing vorticity (10^{-4} sec^{-1}, solid thin lines) corresponding to fig. 7. At maximum value, absolute vorticity is about 10 per cent greater than shearing vorticity. Computations in section 4 of text were made for point marked A in this figure and figs. 7, 8 and 11. J indicates center of jet stream.

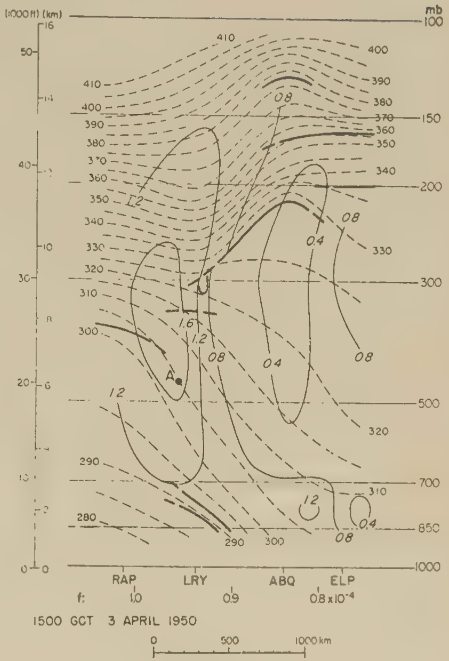

Fig. 11. Potential temperature and vorticity corresponding to fig. 8.

From the charts and cross sections over a 24-hr period, the rate of progression of the "delta" region of the frontal layer was found to be about 30 kn, somewhat less than the wind speed near the cold boundary of the frontal layer in the upper troposphere. At the points indicated on figs. 10 and 11, the actual mean wind speed is about 60 kn. Hence, the speed of air movement relative to the moving delta was about 30 kn. Since the cross sections are located about 275 mi apart in the central part of the frontal layer, a time of 8 hr is required for a particle leaving the marked point on fig. 10 to arrive at a point where the structure is equivalent to that shown in fig. 11. This time is used in computation of the individual derivatives in the last column of table 1, which also gives initial and final values of the various quantities measured directly from the cross sections, and the mean values used in the computation.

As pointed out above, the unknowns D_{zy}, $\partial v/\partial y$, $\partial w/\partial y$ and $\partial v/\partial z$ can, in principle, be obtained by a solution of the four simultaneous equations (6) to (9). In practice, the solution thus obtained is quite sensitive to the exact evaluation of the coefficients in the equations, and in fact gave verifiably unreasonable results (*e.g.*, for $\partial v/\partial y$) in the present case. It is therefore necessary to apply a constraint to one of the terms on the right-hand side. The rate of contraction, measured by $\partial v/\partial y$, is the only one of the above four quantities whose limits can be estimated directly. The assignment of a specific value of $\partial v/\partial y$ overdetermines (6) to (9). These equations were accordingly solved by the method of least squares, and the results are given in table 2 for several values of $\partial v/\partial y$.

At 500 mb (fig. 3), the temperature gradient along streamlines varies between the cross sections; depending upon where it is measured, the axial temperature gradient may be 1 to 2C in 450 km. In the body of table 2, a value for θ_x of 1.25 K per 300 km, corresponding to a mean value of this temperature gradient,

TABLE 1. Measured values and computed changes of various quantities.

Quantity	Initial value	Final value	Mean value	Total change	d/dt (sec^{-1})
θ_y (deg/m)	-6.8×10^{-5}	-2.8×10^{-5}	-4.8×10^{-5}	$+4.0 \times 10^{-5}$	$+1.39 \times 10^{-9}$
θ_z (deg/m)	8.7×10^{-3}	3.9×10^{-3}	6.3×10^{-3}	-4.8×10^{-3}	-1.67×10^{-7}
σ (sec^{-1})	17.0×10^{-3}	7.8×10^{-3}	12.4×10^{-3}	-9.2×10^{-3}	-3.19×10^{-7}
ζ_s (sec^{-1})	2.15×10^{-4}	1.70×10^{-4}	1.92×10^{-4}	—	—
ζ_a (sec^{-1})	2.40×10^{-4}	1.85×10^{-4}	2.12×10^{-4}	-0.55×10^{-4}	-1.91×10^{-9}

has been used. The last column of table 2 gives the range of results for the extreme values of θ_x (positive values corresponding to a greater increase in temperature downstream). The range of variations due to this probable error of estimate is small, in no case changing the sign of $\partial v/\partial z$ or $\partial w/\partial y$.

From the angle of difluence of the contours in the exit region and the relative wind speed, a value of $\partial v/\partial y = 0.75 \times 10^{-5}$ sec^{-1} would be obtained if the streamlines followed the contours. A deviation of the strongest winds 10 deg to the right of the contours, with no deviation of the winds on the cold side of the polar front, would give about twice this amount. In view of the relatively weak decrease of geostrophic wind downstream, this is probably not exceeded. The most probable value of $\partial v/\partial y$, therefore, lies around 1 or 1.5×10^{-5} sec^{-1}, and the computed quantities in column 4 or 5 of table 2 are therefore most likely to be correct. A mean of the values in these columns is used in the following relative evaluation of the terms:

$$\frac{d}{dt}\theta_y = -\frac{\partial u}{\partial y}\theta_x - \frac{\partial v}{\partial y}\theta_y - \frac{\partial w}{\partial y}\theta_z, \tag{6a}$$

$$+1.39 \approx +0.41 + 0.60 + 0.54 \quad (10^{-9}\ \text{deg m}^{-1}\ \text{sec}^{-1});$$

$$\frac{d}{dt}\theta_z = -\frac{\partial u}{\partial z}\theta_x - \frac{\partial v}{\partial z}\theta_y - \frac{\partial w}{\partial z}\theta_z, \tag{7a}$$

$$-1.67 \approx -0.52 - 0.97 + 0.20 \quad (10^{-7}\ \text{deg m}^{-1}\ \text{sec}^{-1});$$

$$\frac{d}{dt}\zeta_a = -\zeta_a D_{xy} + \frac{\partial w}{\partial y}\frac{\partial u}{\partial z}, \tag{8a}$$

$$-1.91 \approx -0.67 - 1.07 \quad (10^{-9}\ \text{sec}^{-2});$$

and

$$\frac{d}{dt}\sigma = -\sigma D_{xz} + f\frac{\partial v}{\partial z} - f\frac{\partial v_g}{\partial z} - \frac{\partial v}{\partial z}\frac{\partial u}{\partial y}, \tag{9a}$$

$$-3.19 \approx +1.55 - 1.89 - 1.35 - 1.97 \quad (10^{-7}\ \text{sec}^{-2}).$$

The error of agreement between the sum of terms on the right-hand sides, and the total observed changes on the left, varies from 9 per cent in (8a) to 23 per cent in (7a). These discrepancies are clearly within the error of synoptic evaluation, and it would be misleading to adjust the values until complete agreement is reached. It should be pointed out, however, that hydrostatic consistency interrelates the various quantities in table 1 in such a manner that a large error of estimate of one quantity is likely to result also in nearly proportionate errors in the others, and this stabilizes the solution.

In accomplishing changes of the horizontal temperature gradient, the first term of (6a), involving more rapid cold advection by the stronger winds on the warm-air side of the front than by the weak winds on the cold-air side, is of nearly equal magnitude with the second term involving lateral difluence, and clearly must be considered when dealing with horizontal advective processes in frontal layers. The "entrance" zones of such frontal layers are commonly associated with warm advection, and the "exit" zones with cold advection. This being the case, weak confluence or difluence of isobaric contours cannot in itself be taken as an indication that horizontal advection is unimportant in changing the temperature gradient. The third term of (6a), involving upward motion and adiabatic cooling of the air on the warm- relative to the cold-air side of the front, contributes a significant but not overwhelming amount to frontolysis of θ_y. In the example of strong frontogenesis given by Reed and Sanders (1953), this term was found to account entirely for frontogenesis in the horizontal temperature field.

In (7a) for the change in thermal stability, the first term (involving differential rates of advection due to stronger winds at higher elevations) is again not negligible, accounting for a third of the observed change in stability. The second term, involving differential transverse advection (in the y-direction) at different levels, contributes the greatest amount to the stability

TABLE 2. Least-squares solutions of (6) to (9).

$\partial v/\partial y \approx -D_{xz}$ (sec^{-1}):	-10^{-5}	0	$+10^{-5}$	1.5×10^{-5}	2×10^{-5}	*
$D_{xy} \approx -\partial w/\partial z$ (10^{-5} sec^{-1}):	−0.71	−0.25	+0.20	+0.43	+0.66	±0.12
$\partial v/\partial z$ (10^{-3} sec^{-1}):	−0.59	−1.22	−1.85	−2.17	−2.49	±0.23
$\partial w/\partial y$ (10^{-7} sec^{-1}):	−2.59	−1.82	−1.05	−0.66	−0.28	±0.21

* See text.

change,[6] while the vertical contraction (last term) contributes a small amount counter to the sign of the observed change in θ_z.

The decrease of vorticity about a vertical axis, according to (8a), is accomplished predominantly by the vertical-motion vertical-shear term, although a little more than one-third of the total change is produced by divergence. In the case presented by Reed and Sanders (1953), the increased vorticity during frontogenesis was produced entirely by the vertical shear term.

In (9a) for changes in vertical shear, all terms are of roughly the same magnitude, the first term [analogous to the first term in (8a)] being the only one contributing to an increase rather than a decrease of vertical shear. The other terms may be combined in two ways for simple physical interpretation. Combining the second and third terms, we have

$$f\frac{\partial}{\partial z}(v - v_g) - \frac{\partial v}{\partial z}\frac{\partial u}{\partial y} = \frac{\partial}{\partial z}\left(\frac{du}{dt}\right) - \frac{\partial v}{\partial z}\frac{\partial u}{\partial y}$$
$$= (-3.24 - 1.97)(10^{-7}\ \mathrm{sec}^{-2}).$$

In this way, the combined terms may be visualized as the variation with height of the axial acceleration of wind speed due to variation of the non-geostrophic v-component (normal to the wind direction at the level considered) with height, and the last term represents the differential transverse advection of the existing wind speeds at different levels.

Alternately, the second and fourth terms of (9a) may be combined to give [*cf.* (4)]

$$\frac{\partial v}{\partial z}\left(f - \frac{\partial u}{\partial y}\right) - f\frac{\partial v_g}{\partial z} = \zeta_s\frac{\partial v}{\partial z} - \frac{\partial}{\partial z}\left(\alpha\frac{\partial p}{\partial x}\right)$$
$$= (-3.86 - 1.35)(10^{-7}\ \mathrm{sec}^{-2}).$$

In this case, the combined terms may be visualized as a "rotation" toward the horizontal of the shearing vorticity about a vertical axis as an air column is tilted laterally. The remaining term is then analogous to a solenoidal term, tending to produce a circulation acceleration about the y-axis.

Note that in the delta region $\partial v/\partial z$ is negative (wind veering with height), although the isotherms (fig. 3) indicate a backing of the geostrophic wind with height. In (7a), the term $(\partial v/\partial z)\theta_y$ accounts for the major part of the observed change in θ_z. If $\partial v/\partial z$ were zero or positive, the observed change in θ_z would require a very strong temperature-advection field (first term) and/or pronounced convergence (last term) as the air leaves the frontal layer. Likewise in (9a), a zero or positive value of $\partial v/\partial z$ would require a large value of $\partial v_g/\partial z$ (third term).

From (9a) it is readily seen that it would be impossible to account for the observed change of vertical wind shear except by nongeostrophic motions, under the observed conditions. In the case of geostrophic balance, the second and third terms of (9a) would cancel, and with the observed temperature distribution and difluence in the exit zone both the first and the last terms would in that case be positive, while the total change in σ is actually negative. Since generation or dissipation of vertical wind shear is a necessary characteristic of frontogenesis or frontolysis, it follows that the formation or dissolution of frontal layers is *essentially* a non-geostrophic process.

It being recognized that there is some latitude in analyzing a cross section from a given set of soundings, the degree of concentration of the frontal layer in fig. 7 was varied the maximum possible amount consistent with the observations. Neither this, nor individual modification of the values in table 1 by 25 per cent, resulted in changing the general results of the computations. Since the particular frontal system studied had a structure characteristic of upper-troposphere fronts, these results (aside from exact numerical magnitudes) are regarded as having general validity for the high-level frontogenetic or frontolytic process.

5. Lower-level frontogenesis

As mentioned earlier, the high-level frontal delta is of particular interest because of its frequent association with low-level cyclogenesis or frontogenesis. Some remarks are therefore in order regarding the sequence of events in lower levels near the time discussed above.

Near the earth's surface, where vertical motions are damped, the terms $\theta_z\,\partial w/\partial y$ in (6) and $\sigma\,\partial w/\partial y$ in (8) are ineffective. Hence, frontogenesis in the horizontal temperature field is accomplished by horizontal advective processes in the manner discussed by Bergeron (1928) and Petterssen (1936), while vorticity changes can only be effected by horizontal divergence and friction. Frontogenesis in the surface temperature field is usually accompanied by increased vorticity. The connection between surface frontogenesis, vorticity increase, and convergence has been established synoptically by Petterssen and Austin (1942).

In addition to changing properties in a horizontal plane, frontogenesis implies increased vertical stability and shear. Since increased vorticity in surface layers is associated with convergence, (7) implies that unless $\theta_z\,\partial u/\partial z$ is the controlling factor the required increase in stability can only be accomplished if $\partial v/\partial z > 0$, that is, the horizontal branch of the circulation must be in a direct solenoidal sense. Such a circulation simultaneously contributes to increased vertical shear to balance the intensified horizontal temperature gradient.

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[6] It should be noted that, at a wind speed of 60 kn, a value of $\partial v/\partial z = 2 \times 10^{-3}\ \mathrm{sec}^{-1}$ would ordinarily not be detectable in coded wind observations, since a directional shift of less than 5 deg/km vertically could account for a transverse shear component of this magnitude.

Although not all the above factors can be readily studied, low-level frontogenesis east of the Rocky Mountains between 0300 GCT and 1500 GCT 3 April 1950 affords a good example of the ideal frontogenetic deformation field. At 0300 GCT 3 April (fig. 12), there was a moderately strong temperature gradient at 850 mb over the north-central United States. Although some soundings showed diffuse stable layers, there was at this time no organized and distinct frontal layer such as shown by the 850-mb chart (fig. 2) and cross sections (*e.g.*, fig. 9) 12 hr later.

Both at 0300 and 1500 GCT, there was an ideal deformation field in the form of a col with a low center to the left of the thermal concentration over the Great Lakes and another low to the right of this concentration over the central great-plains states. From the winds over Illinois and Western Kansas, the mean rate of dilatation along the isotherms appears to be about 45 kn in 1300 km, or 1.8 m/sec per 100 km.

At 0300 GCT, the mean temperature gradient over a belt 300 km wide was about 3C per 100 km. If it is assumed that the above dilatation was approximately balanced by contraction across the isotherms,

$$\frac{\delta}{\delta t}\left(\frac{\partial T}{\partial y}\right) \approx -\frac{\partial v}{\partial y}\frac{\partial T}{\partial y}$$

$$= -(-1.8 \times 10^{-5})(-3 \times 10^{-5})$$

$$= -5.4(10^{-10}\ \text{deg m}^{-1}\ \text{sec}^{-1}),$$

corresponding to an increase in temperature gradient at the rate of 2.3C per 100 km per 12 hr. By 1500 GCT 3 April 1950, the mean temperature gradient in the frontal zone had actually increased to about 5C per 100 km, in fair agreement considering the crudity of estimates. Hence, the frontogenesis at 850 mb could be accounted for mainly by horizontal advective processes (though effects of vertical motions are not entirely negligible). This frontogenesis was most pronounced near the surface and decreased markedly aloft, the front extending upward only to around 650 to 700 mb (figs. 8 and 9) and having only weak horizontal temperature gradients in the upper part.

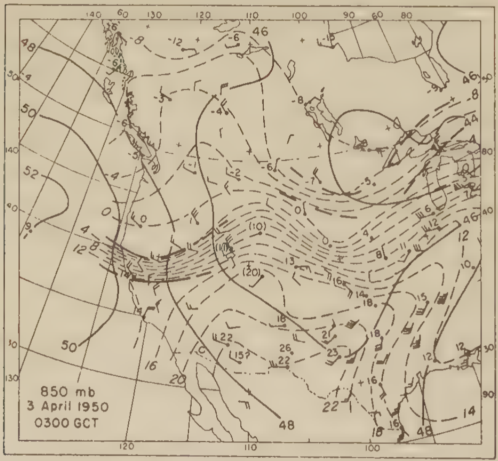

FIG. 12. 850-mb chart, 0300 GCT 3 April 1950. Dashed heavy lines indicate indistinct stable layers.

It would be difficult to imagine that the high-level front, which was still well to the west at 0300 GCT 3 April 1950, was entirely responsible for the low-level frontogenesis which occurred prior to that time. The circulation systems responsible for the frontogenetic deformation field had already been existent for some time earlier. The significance of the higher-level frontal system appears to lie in the fact that (as is commonly observed), when the high-level front moved eastward over the lower-level front, the two combined into a single pronounced frontal layer extending from the surface to the tropopause level. Thus, the available low-level air-mass contrasts were drawn into the circulation system of the deep tropospheric front. As suggested by Bjerknes (1951), removal of air from lower levels must be an essential feature of surface frontogenesis. As Bjerknes has shown, the lower levels of a deep-tropospheric front of the type discussed in this article are characterized by weak inertia stability, which is favorable for large displacements along isentropic surfaces and thus for a connection between the low-level and high-level frontal circulations.

6. Generalized circulations in delta region

Computations of the kind in section 4 gave, at all levels above about 600 mb, gradients of vertical and transverse motions of the same signs as indicated by the specific example in that section. At lower levels, complex variations of frontal structure precluded such computations. Fig. 13 shows schematically the distribution of vertical and lateral motions, in a cross section through the high-level frontal delta, deduced from the results of section 4. Unless otherwise specified, the following discussion refers to the components of circulation within the frontal layer or the stratosphere below the level of maximum wind. Above the maximum-wind level, where the horizontal temperature gradient and vertical shear change sign, the same discussion applies, provided the signs of $\partial w/\partial y$ and $\partial v/\partial z$ are reversed.

Within the front, the vertical motions in fig. 13a contribute, through differential adiabatic cooling rates across the front, to frontolysis of the horizontal temperature field at all levels except the surface and maximum-wind levels. The effects on vorticity changes are more complex and will be discussed in some detail. At the level of strongest wind, the term $\sigma\ \partial w/\partial y$ in

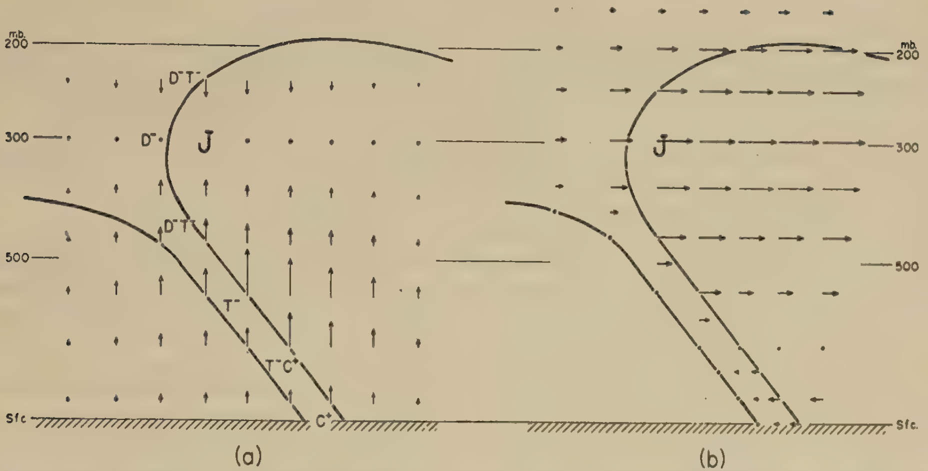

FIG. 13. Schematic distribution of (a) vertical motions and (b) lateral motions in cross section through frontal delta (corresponding to frontolysis, except at low levels; for frontogenesis, reverse direction of arrows). In (a), regions where convergence (C), divergence (D), and tilting of vortex tubes (T) are important in changing vorticity are indicated by appropriate letters, with superscripts indicating sign of contribution to vorticity change.

(8) is zero. A divergence of about 1.2×10^{-5} sec^{-1} was computed from vorticity changes just to the left of the jet axis.[7] If zero vertical motion is assumed at maximum-wind level, this means descent above and ascent below. In view of the sign of $\partial w/\partial y$ computed earlier, the only possible combination of vertical motions is that indicated in the upper-troposphere levels of fig. 13. From the relative magnitudes of D_{xy} and $\partial w/\partial y$ in table 2, it follows from geometrical considerations that ascending motions increase in magnitude at lower levels, particularly on the warm-air boundary of the front. Since $w \approx 0$ at the earth's surface, there must be a level of maximum upward motion somewhere in the middle troposphere. In the frontogenesis computations made by Reed and Sanders (1953), strongest vertical motions on the warm-air frontal surface were evidently observed near 550 mb.

Vertical motions of the type indicated in the upper part of the frontal layer are only compatible with vertical stretching and horizontal convergence in the central and lower parts of the front. The relative (and combined) effects of divergence and tilting ($\partial w/\partial y$) upon vorticity changes clearly vary in different parts of the frontal layer. The general regions where divergence (D), convergence (C), and tilting (T) contribute to vorticity changes are indicated in fig. 13a. As one progresses downward in the frontal layer, the high-level divergence gradually changes to convergence, which contributes to individual increases of vorticity. At the same time, the effect of the tilting term increases in its contribution to decrease of vorticity, down to some mid-troposphere level. In the lower part of the frontal layer, both effects decrease downward; however, near the surface, where the tilting term vanishes, there must still be convergence which leads to net individual increases of vorticity. Below some level between 700 and 850 mb, the westerly wind component is less than the eastward speed of the high-level exit region, so that in fact the frontal layer overtakes the air particles in lower levels, which actually undergo individual increases in vorticity, compatible with fig. 13a.

The existence of general ascent as indicated in fig. 13a is verified by the distribution of dewpoint depressions at 500 mb (fig. 14). This pattern was relatively

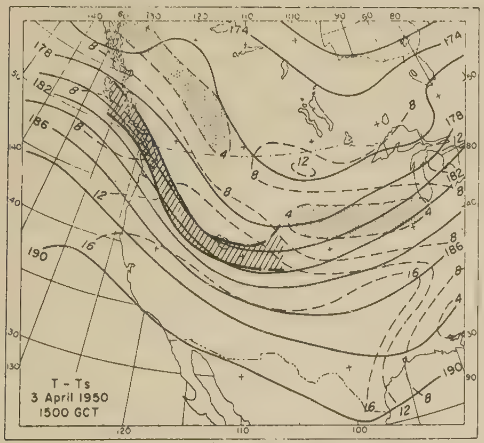

FIG. 14. Dewpoint depressions (temperature minus dewpoint, dashed lines) at 500 mb, 1500 GCT 3 April 1950. Areas of dewpoint depression less than 4C stippled; frontal layer hatched. Thin solid lines: contours of 500-mb surface.

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[7] Because of the strong lateral gradient of stability in the cyclonic shear zone at jet level, it is generally impossible to make accurate direct estimates of the divergence from stability changes along trajectories. Also, at finite distances above and below jet level, where $\theta_v\, \partial v/\partial z \neq 0$, lateral tilting of air columns may cause a net decrease in stability although increased stability is indicated by the divergence.

conservative and moved eastward with the frontal delta at a speed less than that of the winds, indicating ascent both north and south of the frontal zone. Further upstream, beneath the well-developed portion of the frontal layer, observations in the cold as well as the warm air indicated relatively low humidities, although moist air was found several hundred kilometers north of the front. Analyses of the temperature-dewpoint depression in cross sections through distinct frontal layers (Vuorela, 1953) show very pronounced maximum depressions in the middle troposphere. On the basis of this observation, Vuorela concluded that frontogenesis in middle and high levels is accompanied by subsidence on both sides of the front.[8] Direct evidence of this is provided by the vertical motions during frontogenesis shown by Reed and Sanders (1953).

The lateral motions in the exit region (fig. 13b) are sketched on the basis of the computations in section 4, which showed that in the upper part of the frontal layer motions of this type accounted for the larger part of the changes in both vertical stability and vertical shear. In the lower part of the frontal layer, where as noted above individual frontogenesis is undergone by particles overtaken by the frontal layer, a transverse shear component of the opposite sign is suggested.

Within the warm air mass outside the front, the magnitude of lateral motions is shown as increasing toward the right, to satisfy continuity with the vertical motion field and with observed axial velocity gradients (wind speed decreasing downstream). Strong difluence above and south of the frontal surface (fig. 3) is characteristic of this type of situation. Inside the frontal layer, the distribution of $\partial v/\partial z$ shown in fig. 13b is only compatible with difluence in the higher-level delta region. In lower levels, lateral contraction is indicated to account for individual frontogenesis of the temperature field of air particles overtaken by the frontal layer.

The above discussion has been concerned mainly with the sense of the circulation components within the frontal layer proper. If vertical motion is assumed zero at some distance away from the front, it is clearly implied (fig. 13a) that the horizontal gradient of vertical motion in the warm air mass is opposite in sense to the gradient of vertical motion within the frontal layer. Thus, in the warm air mass south of the frontal delta, the terms in $\partial w/\partial y$ contribute to increased vorticity (mainly on the anticyclonic-shear side of the jet stream where the vorticity actually does increase), and at the same time tend to increase the horizontal temperature gradient. Since the thermal stability is weak outside the front, the contribution of this effect to changes in θ_v is undoubtedly small and more than offset by the pronounced difluence or confluence observed outside the frontal layer.

It is important to note that the magnitudes of all terms in (6) to (9) involving $\partial w/\partial y$ and $\partial v/\partial z$ depend upon the coefficients of the latter quantities. As a rule, the vertical shear, vorticity, and vertical and horizontal potential temperature gradients are considerably weaker on the anticyclonic than on the cyclonic-shear side of the jet stream, and consequently the corresponding terms in (6) to (9) effect comparatively small changes of the various properties on the right-hand side of the jet. Likewise, the association of divergence in (7) and (8) with relatively weak stability and particularly with low vorticity on the right of the jet implies that divergence should be relatively ineffective in changing these quantities.

It will be noted that, although all other features of the wind and temperature fields can be accounted for at least qualitatively by the motions indicated in fig. 13, this scheme does not properly account for vorticity changes at the maximum-wind level on the right-hand side of the jet. Here the divergence indicated in the delta region should produce individual decreases of vorticity, while in fact the opposite change presumably occurs. It is well known that the level of maximum wind does not remain constant, so it is possible that vorticity variations at this level are due to vertical motions of some more complicated nature. It should be pointed out that the existence of near-zero absolute vorticities often observed on the right flank of the jet stream could not in any event be accounted for by divergence processes, since divergence becomes ineffective in changing vorticity when the vorticity itself is low.

Finally, some remarks should be made on the combination of motions in figs. 13a and 13b from the standpoint of continuity. Simultaneous vertical stretching and lateral divergence, such as indicated in the central part of the frontal layer in fig. 13, are clearly incompatible with continuity requirements, *if* conditions only in this one cross section are considered. However, if in the continuity equation,

$$\frac{\partial u}{\partial x} = -\left(\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) - \frac{1}{\rho}\frac{d\rho}{dt},$$

the last term is at first assumed zero, and $\partial w/\partial z = \partial v/\partial y = 10^{-5}$ sec^{-1}, continuity is satisfied if $\partial u/\partial x = -2 \times 10^{-5}$ sec^{-1}, corresponding to a decrease of 2 m/sec per 100 km along a streamline. With a wind speed of 60 kn in a velocity field moving at a rate of 30 kn, this amount of deceleration can be accomplished by a cross-contour component of less than 5 deg. In addition, since in the delta region the air is rising, $\rho^{-1}\, d\rho/dt < 0$, and with vertical motions of 2 cm/sec can amount to -0.2×10^{-5} sec^{-1} near 500 mb, contributing a small amount partly to compensate $\partial v/\partial y + \partial w/\partial z$.

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[8] Although the most strongly-developed parts of high-troposphere fronts seem to be generally characterized by dryness, weaker but still distinct portions of the same fronts often show high humidities in upper levels. As noted by Miller (1948), the horizontal *gradient* of vertical motion is the important factor in changing intensity of a frontal layer, and frontogenesis or frontolysis can occur either with ascending or descending motions. The vertical motions accompanying frontogenesis clearly cannot be considered out of context with existing synoptic disturbances which may control the sign of vertical motions.

Obviously the practice of attempting to satisfy continuity by balancing motions in one cross section can be very misleading. Thus, for examples, Namias and Clapp (1949) and Murray and Daniels (1953) have shown that in the region of jet intensification (confluence or entrance zone) the horizontal branch of the circulation must be in a direct solenoidal sense, and have postulated that this branch is compensated by vertical motions in the same sense, *i.e.*, ascent on the right and descent on the left of the jet in the troposphere. Recent observational studies suggest that no such simple relationship between vertical and transverse motion exists. In a study of difluence over Europe, Hubert (1953) found strongest rising motions in the middle troposphere to the right of the decelerating jet (indirect horizontal motions, direct circulation in vertical motions). Investigations by Reed and Sanders (1953), and Newton and Carson (1953), indicate that the vertical motions most significant for intensification of the thermal and vorticity fields during frontogenesis and jet-stream formation are in an indirect solenoidal sense, in agreement with the suggestion by Rossby (1947) that formation of the jet must be accompanied by a dynamic concentration of solenoids through vertical motions of this character (see also discussion by Palmén and Nagler, 1949).

7. Conclusion

Free-atmosphere frontogenesis and frontolysis must, as suggested by Miller (1948), be regarded as a three-dimensional process. This process involves a number of different mechanisms, whose importance varies at different levels. The major parts of variations in wind and temperature fields during frontogenesis and frontolysis may be regarded as taking place simultaneously in such a manner that the same motions are responsible for changing both fields.

Near the earth's surface and near the maximum-wind level, divergence and thermal advection in the classical horizontal deformation fields predominate in contributing to frontogenesis, while the influence of vertical motions is most important in the middle troposphere. At all levels (except near the maximum-wind level), vertical variations in *non-geostrophic* wind components normal to the wind direction are most significant in producing changes of the vertical shear and stability. Analysis of the three-dimensional field of motion shows that, although the confluence mechanism (Namias and Clapp, 1949) directly accounts only partly for concentration of the temperature field in the middle troposphere, it is an essential feature linked with vertical as well as horizontal variations of the wind field (fig. 13b) without which frontogenesis could not occur.

Sherman (1953) has recently suggested that the field of vertical motions might be deduced from mid-troposphere vorticity variations, on the basis that these variations are controlled mainly by gradients of vertical motion rather than by divergence. The scheme in fig. 13a indicates that deductions on this basis may differ in some fundamental respects from the vertical motions deduced from vorticity changes at the maximum-wind level alone. In particular, the field arrived at shows ascending motions on both flanks of the jet stream. It is often observed, as in the case analyzed above, that low-level cyclogenesis in the delta region occurs on the right flank of the jet stream, with precipitation on both flanks.

The relation of high-troposphere frontogenesis and frontolysis to surface cyclogenesis is complex and far beyond the scope of this article. The synoptic example discussed above is of a very restricted nature, in that the high-troposphere front was oriented nearly parallel to the upper flow. Hence, the field of vertical motions deduced for this case cannot be generalized to cover all synoptic situations associated with high-level frontal variations. Nevertheless, this treatment suggests, in line with the philosophy emphasized by Prof. E. Palmén, that the study of high-level frontal layers and their variations offers a fertile field of research which should eventually prove of real value in practical forecasting.

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Contribution No. 728

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Further measurements of the sound scattering properties of several marine organisms

PAUL FERRIS SMITH

Summary—Investigations of underwater sound scattering by marine organisms have been continued under more favourable operating conditions and using improved instrumentation. The results corroborate and extend those obtained and reported earlier that shrimp as well as fish and squid are effective sound scatterers. The present data also include measurements of scattering by as few as one large shrimp. The results of fish, squid and large shrimp are analyzed to give the effective scattering area of each over a frequency range of from 8 Kc. to 30 Kc. Assuming an idealized layer an estimate is made using these values of the number of scatterers of each type necessary to account for the volume reverberation reported for the deep scattering layer.

INTRODUCTION

Using a modified form of the experimental technique developed and reported earlier (SMITH, 1951) for quantitive echo ranging over short distances at various frequencies, a series of sound scattering measurements have been made on squid (*Loligo pealei*), scup (*Stenotomus versicolor*), sea bass (*Centropristes striatus*), and shrimp (*Palaemonetes vulgaris* and *Penaeus setiferus*). The purpose of these measurements was to determine the dependence of acoustic cross section of possible marine scatterers upon frequency of the sound and the size and structure of the scatterer. This information is required in evaluating the several biological hypotheses (CHAPMAN, 1947 ; HERSEY and MOORE, 1948 ; LYMAN, 1948 ; MOORE, 1948 ; 1950) for the origin of the deep scattering layer and will also provide some quantitive information to assist the development of acoustic ranging methods for fish detection. This report describes the instrumentation, method of observation and results obtained.

EXPERIMENTAL TECHNIQUE

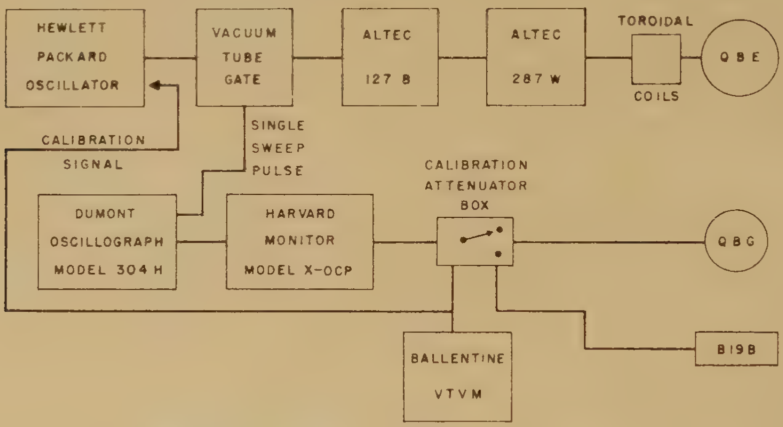
All operations were conducted aboard a 35 × 15 foot raft moored in water 25 feet deep on a fresh-water pond (Flax Pond, East Falmouth, Massachusetts) one-third mile in diameter. The electronic equipment, power for which was supplied by a gasoline generator on shore, was mounted in a 15 × 15 foot house at one end of the raft and the underwater equipment was lowered through a central opening. It was found necessary to surround the raft with a surface-to-bottom net (a used mackeral seine having $\frac{3}{4}''$ mesh was used) and fire electric blasting caps to rid the operating region of unwanted eels and other fish. Attempts to overcome this problem by contamination of the water in the vicinity with sodium hypochlorite or rotenone did not work.

Equipment and Measurements

The echo ranging equipment (Fig. 1) produced one to one-half millisecond pulses of sound over a frequency range from 8 to 31 kilocycles at a repetition rate of about one every half second and received either the direct or backward scattered sound. Additional equipment (Model OCP-1 Sonar Monitor with a CAEK-51112 Transducer) was available to make receiving response calibrations of the transducers. These calibration curves, which do not vary more than ± 1·5 db. from run to run, and the voltage comparison method of calibration were used to determine the intensity of the outgoing pulse and the backward scattered sound by visual observation of an oscilloscope whose sweep was triggered by the transmitted signal.

Experimental Procedure

All measurements were made at a depth of about 3 meters at which was located, on the end of a 1″ pipe, the QBE (transmitting) and the QBG (echo-receiving) transducers. This rig could be rotated so as to echo from a scatterer at this same depth and at a range from one to two meters. Due to the construction of the raft it was found most desirable to operate at a range of 1 m. After finding that the positioning of the echoer was very critical at this close range, a series of echo directivity patterns were taken to make certain all scatterers used were placed within the volume of water for which no directivity correction was necessary. At this 1 m range, an area 17 × 21 cm centered normal to the horizontal axis of the sound path defined the limit in which the echo had not fallen off more than 2 db with respect to that from an echoer directly on the axis. It was decided that, with a calibration reproducibility of ± 1·5 db, no directivity correction would be required for scatterers restricted to this plane. Care was taken not to use scatterers or arrays of scatterers that extended beyond these dimensions. To assure centering of any scatterer within this area, the depth of the scatterer and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PACKARD
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TOROIDAL
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CALIBRATION
SIGNAL
SINGLE
SWEEP
PULSE
CALIBRATION
ATTENUATOR
BOX
DUMONT
OSCILLOGRAPH
MODEL 304 H
HARVARD
MONITOR
MODEL X-OCP
QBG
BALLENTINE
VTVM
B19B

Fig. 1. Echo ranging Equipment block diagram.

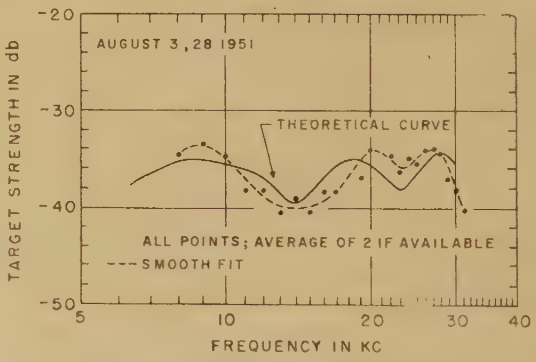

Fig. 2. Target strength of brass sphere.

the orientation of the QBE-QBG rig were varied until the maximum echo was received. The outgoing pulse was measured by placing the B-19-B hydrophone at this same point by the same method.

The method of supporting the scatterers might well affect the results ; it was carefully investigated at the outset. In every case, the scatterer under observation was supported by one or more vertical 0·014″ diameter stainless steel wires 6 m long weighted at the lower end. Scattering measurements over the frequency range 8 to 30 Kc. were made on all of these bare supporting wires to determine their contribution to the total scattered sound when the scatterer was present. This is called the background scattering. The background target strengths measured for one, two, ten, twenty and fifty of the 0·014″ diameter stainless steel supporting wires were not significantly different. This was due in part to their failure to show above the scattering observed when no wires were present and to their rather large variability (± 4 db.) from one frequency setting to the next. In consideration of this, a composite average of all these background measurements was made ; this is plotted on all figures showing background target strength. With this average curve is plotted a dotted line connecting the maximum background scattering values obtained at each frequency (see Figs. 3, 5, 7, 8, and 10).

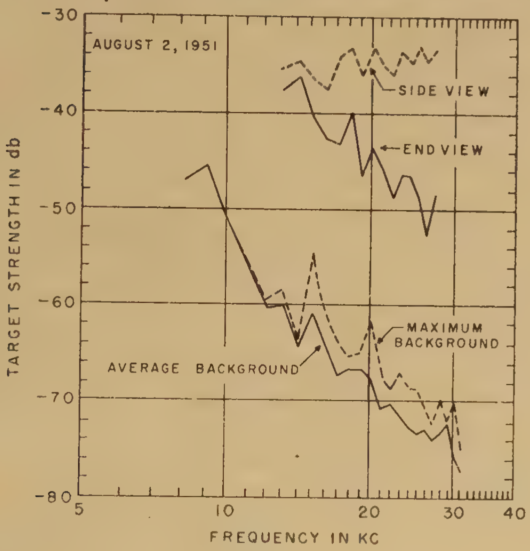

Fig. 3. Target strength of sea bass.

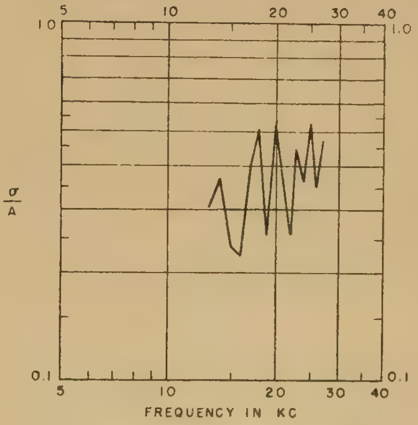

Fig. 4. Variation of effective target area with frequency-for Sea bass.

To test reliability of the experimental procedure, the scattering by a 6·17 cm diameter solid brass sphere was measured, since its scattering can be computed from theory. A comparison of theory and experiment shows agreement quite satisfactory for the present purposes (Fig. 2), the experimental values lying within 2 db. or less of the theoretical curve.

To elimate air bubbles on or in the scatterers, all scatterers were placed in water in a vacuum dessicator and held at a pressure of about 1 cm. of mercury for at least one hour and then attached to the supporting wires without exposure to air. To further safeguard against the formation of air bubbles of films whenever a hydrophone or metal echoer was lowered into water, they were washed with a detergent and detergent was sprinkled on the surface of the water through which they passed. Despite the precautions to eliminate air bubbles there is still the possibility that some were present and undetected. A line is therefore drawn on Fig. 8, showing the calculated value one resonant bubble would give at each frequency used. In only one instance (the maximum value at 15 Kc.) does evidence of bubble contamination appear in the background scattering. Results for the specimens (except Fig. 8) would have required a very large number of bubbles conveniently resonant at many frequencies.

The actual area of the scatterer normal to the sound beam was determined by tracing around the scatterer, placed on a piece of paper as it had faced the transducers, and measuring the resulting area with a planimeter.

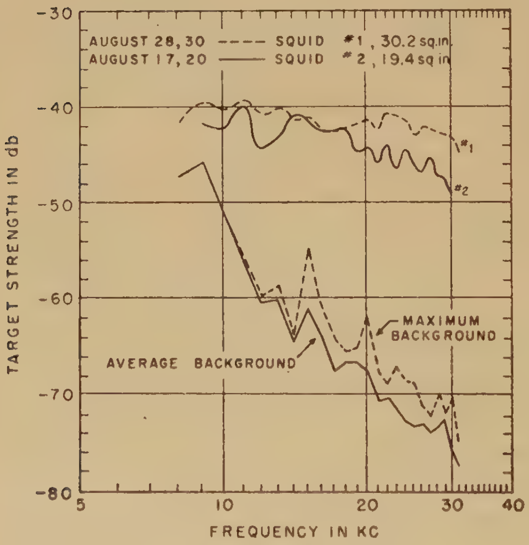

Fig. 5. Target strength of squid.

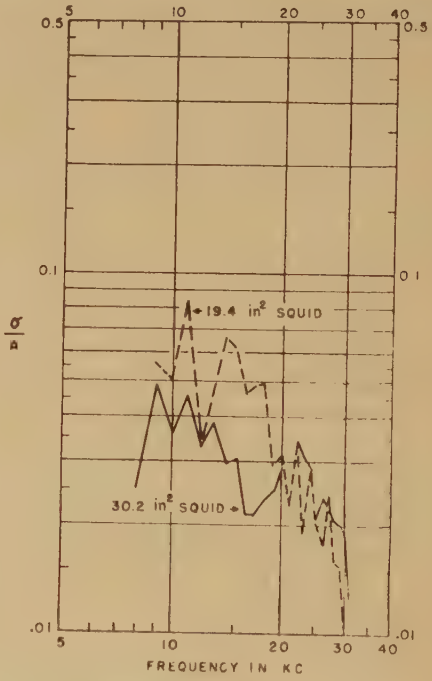

Fig. 6. Variation of effective target area with frequency-for two individual squid.

Precision and Reliability

The purpose of the measurements reported herein was, in part, to repeat, extend, and improve similar measurements made in 1950 and reported earlier (SMITH, 1951). It is felt that this aim has been accomplished. The scattering values obtained from the brass sphere were both more reproducible (less than 1 db variation as compared with 2 db.) and fitted more nearly the calculated values (Fig. 3) than the 1950 data ; The measurements then are probably precise to within 1 to 2 db. since the results do not depend on calibrations other than those that were part of the observations. The rapid pulse repetition rate and the continuous visual observation of the oscilloscope trace placed the observer in more constant communication with the experimental conditions than was possible when using the previous photographic method of recording. In fact, it was by thus observing the echo on the oscilloscope that the definite presence of unwanted fish was detected. These fish were later observed through a water glass from the surface. Other factors that improved the results indirectly by contributing to the ease of operation were the prevailing quiet water conditions on the pond and the simplicity of handing gear on the new raft.

ANALYSIS OF DATA

The ratio of the back scattered sound intensity 1 yard from a scatterer to the sound intensity incident upon it, defined as its Target Strength, was determined for each of the above marine organisms, for the brass sphere and for the bare frames at each kilocycle from 8 to 31 (Figs. 2, 3, 5, 7, 8, 10, and 11).

Since the above definition of target strength is equivalent to

$$T = 10 \text{ Log} \frac{\sigma}{7\pi}$$

where σ is the effective target area, the value of σ for each scatterer is computed, and the ratio σ/A is plotted against frequency (Figs. 4, 6, 9 and 12). A is the actual area of the scatterer normal to the incident sound.

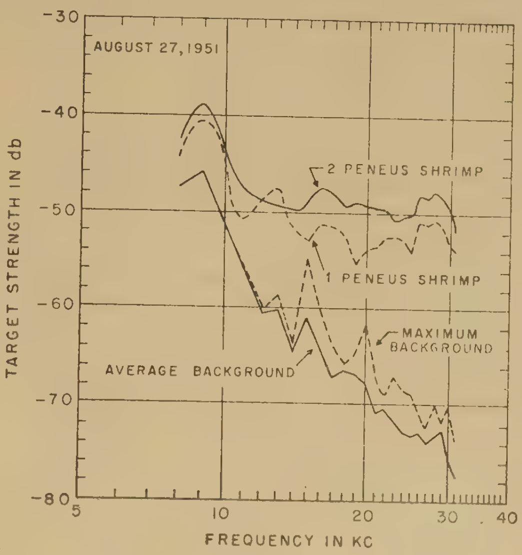

Fig. 7. Target strength of penaeid shrimp.

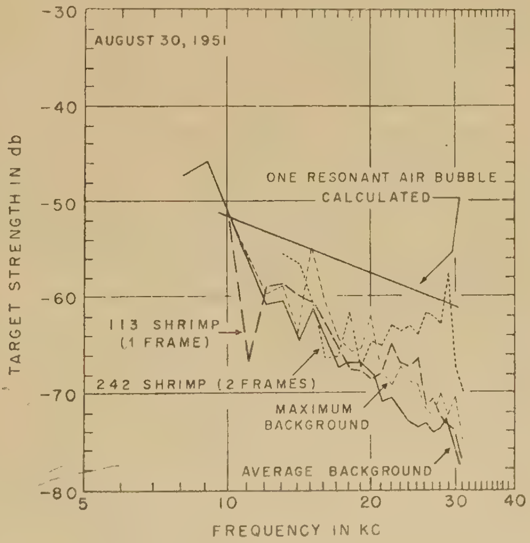

Fig. 8. Target strength of palaemonid shrimp.

To make possible a comparison of the present results with field observations others have made on the deep scattering layer, the quantity scattering cross section per unit volume, called volume scattering coefficient m, is employed. By definition, this may be written

$$m = N \sigma$$

where N is the number of scatterers per unit volume and σ is the effective scattering cross section of each scatterer. Using for convenience the average σ obtained for each scatterer over the range 15 to 25 Kc and reported volume scattering coefficients from the literature, the corresponding number of each type of scatterer per unit volume is computed. These results (Table I) depend upon the value of m for the deep scattering layer. Since the reported volume scattering coefficients (BAZTLER and WESTERFIELD, 1953) differ considerably, two values near the extremes were chosen as noted in the table.

Table I. Scattering cross sections and corresponding population densities to give reverberation levels observed at sea for the various scatterers measured.

Type of Scatterer	*Average σ, yd^2* (15 *to* 25 *Kc*)	*Scatterers/yd^3 to give* m_1 (1)	m_2 (1)
1 Shrimp (*Palaemonetes*)[2]	$2{\cdot}32 \times 10^{-8}$	13	216
1 Shrimp (*Penaeus*)	(3) $6{\cdot}56 \times 10^{-5}$	$4{\cdot}6 \times 10^{-3}$	$7{\cdot}6 \times 10^{-2}$
Scup	$3{\cdot}8 \times 10^{-4}$	$7{\cdot}9 \times 10^{-4}$	$1{\cdot}3 \times 10^{-2}$
Squid #2	$5{\cdot}33 \times 10^{-4}$	$5{\cdot}6 \times 10^{-4}$	$9{\cdot}4 \times 10^{-3}$
Squid #1	$8{\cdot}29 \times 10^{-4}$	$3{\cdot}6 \times 10^{-4}$	$6{\cdot}0 \times 10^{-3}$
Sea Bass	$4{\cdot}4 \times 10^{-3}$	$6{\cdot}8 \times 10^{-5}$	$1{\cdot}1 \times 10^{-3}$

1. $m_1 = 3 \times 10^{-7}$ yd^{-1}, $m_2 = {\cdot}5 \times 10^{-6}$ yd^{-1}.
2. Obtained from an average σ of $5{\cdot}34 \times 10^{-6}$ yd^2 for two groups of 242 and 220 Palaemonetes.
3. This average is for 20 to 30 Kc.

RESULTS

Results and comparisons for the several animal scatterers are given below. All specimens, unless otherwise noted, were alive when taken to the raft and killed shortly before the acoustic measurements were taken.

Sea Bass. The target strength values obtained for one sea bass are shown in Fig. 3. During preliminary observations it was observed that orientation of this scatterer greatly influenced the echo level. Therefore, two runs are shown ; one with the sea bass held broadside to the sound axis, and one with it held parallel to this axis. The ratio of the effective target area (broadside) to actual area is shown in Fig. 4 for each frequency measured.

The two sea bass target strength curves in Fig. 4 approximately span the 1950 data. It is interpreted, therefore, that these two sets of measurements check one another (both fish used were full grown) but that in 1950 the effect of orientation was not investigated.

The high value of effective target area for this scatterer (average $\sigma/A = 0{\cdot}35$) when compared with the squid (average $\sigma = 0{\cdot}03$) suggests that scatterers having heavily calcified endoskeletons with calcified scales (fish) are much more efficient reflectors than those having no scales and noncalcified endoskelton (like squid). While that may be the case, the fact that the value for the effective target area of the scup lies in between the above two (average $\sigma = 0{\cdot}09$) neither wholly corroborates nor invalidates this conclusion.

While it is not believed they have influenced the results, two facts must be noted that may have caused the sea bass values to be high. No net or blasting caps were used to eliminate unwanted fish during this series and the actual area of the sea bass was estimated from the measurement of its length and width. When spurious fish were detected (and they were noted the first day squid were used), the evidence of their presence was rather dramatic on the oscilloscope. It therefore seems highly unlikely that their presence went unnoticed during the earlier sea bass run. The area estimate can be assumed to be off no more than 25% and this would not bring the σ/A values for the scup and sea bass together. Thus, these two factors do not appear to warrant discarding the sea bass data. The difference in the two effective target areas is, therefore, ascribed to physical differences in the fish, but this cannot be verified without further data.

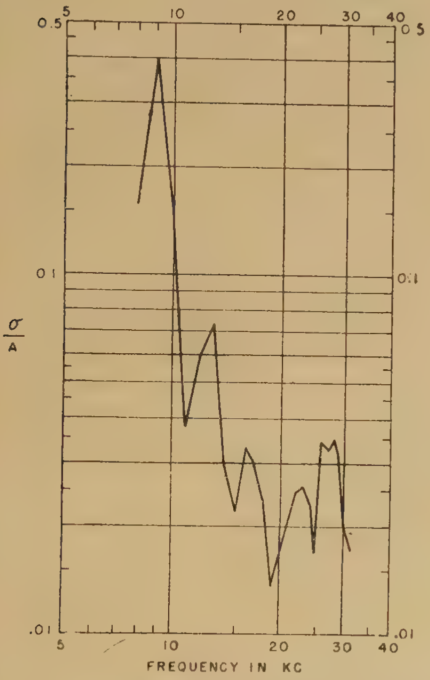

Fig. 9 Variation of effective target area with frequency-for one penaeid shrimp.

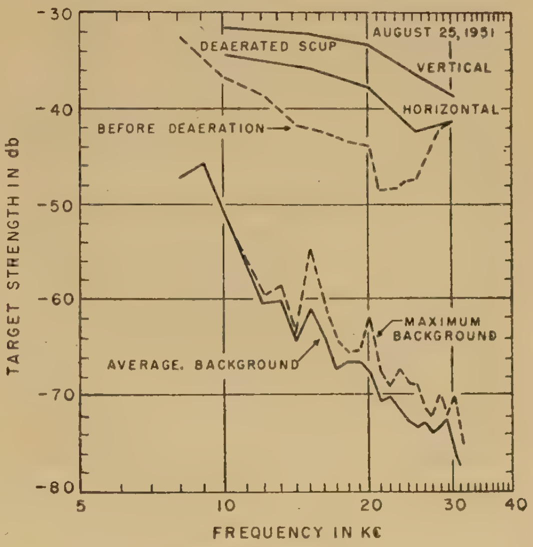

Fig. 10. Target strength of scup. #1.

Squid. Both target strength values (Fig. 5) and the ratio of effective target area to actual vs frequency (Fig. 6) are plotted for two squid having areas of 30·2 and 19·4 in.^{2} respectively. No other comparison will be made between the 1950 results and these because of the unreliability reported for the former data, except to observe that the present values lie between the two earlier sets.

Shrimp. Two readily-available kinds of shrimp, *Penaeus* (these were preserved specimens) and *Palaemonetes*, were used to approximate respectively the red prawns and euphausids that are caught at the depths of the scattering layers. In Figs. 7, 8 and 9 are presented the results of these observations.

Scup. Figs. 10 and 11 give the target strength results obtained from two different scup. These values provide an excellent illustration of the wide range in the intensity of scattering by a single marine target depending both upon its orientation with the sound axis and upon frequency.

In Fig. 10 the dashed curve represents the target strength values for the first scup before deaeration and when supported approximately parallel to the sound axis. This simulates the natural aspect for midwater reverberation received at the surface. The two solid curves connect the values obtained after deaeration and with the scup supported carefully parallel and then normal to the sound axis. The apparent increase after deaeration is ascribed solely to orientation as illustrated by Fig. 11 which gives target strengths for the second scup. Due to equipment failure this scup was not deaerated. The large dependence (over 30 db.) of scattering level on orientation and frequency is clearly evident here. The upper curve was obtained after orienting the scup to give a maximum at 25 Kc. The two points at 15 Kc. represent the maximum and minimum at this frequency. Fig. 12 gives σ/A vs frequency for the average of the two solid curves of Fig. 10. Similar curves for scup #2 have not been computed.

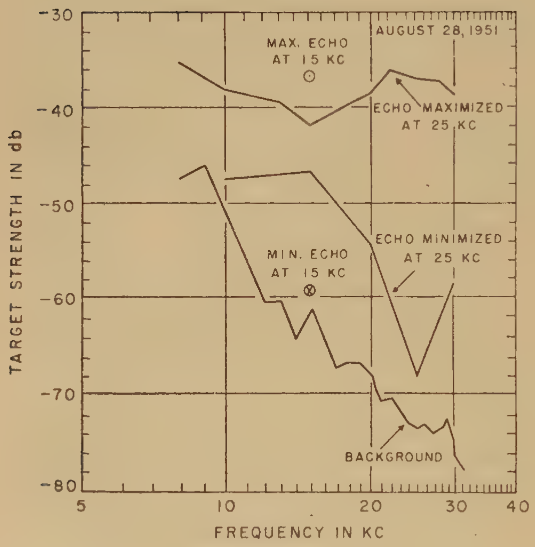

Fig. 11. Target strength of scup. #2.

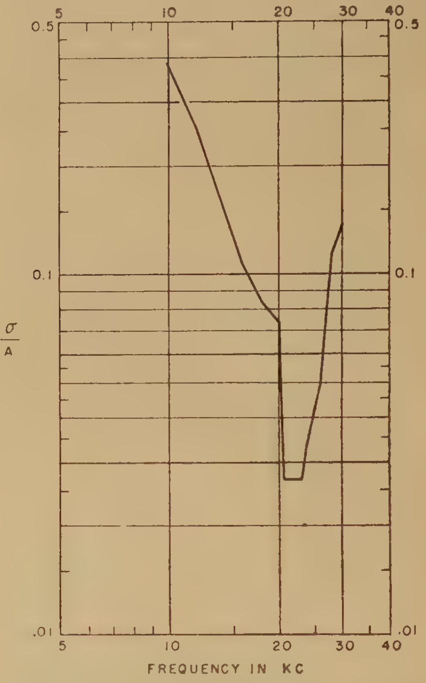

Fig. 12. Variation of effective target area with frequency-for scup (average #1).

DISCUSSION

Table 1 gives the population densities required to account for representative large and small volume scattering coefficients (University of California, Division of War Research, 1946). Considering the restricting assumptions necessary to compute these values of population densities and the inability at present to compare these with absolute population densities, these values are presented with only the comment that they do not conflict with present biological knowledge, except that a population density of 216 yd^{-3} for the palaemonid shrimp is regarded as improbably high.

There is no truly satisfactory way of assessing the physical data on sound scattering since the shape of the specimens precludes any computations of target strength.

Approximately the correct scattering was observed for the brass sphere, and though there may have been gas bubbles present in some of the measurements they have not significantly affected the measurements reported. The effective target areas all vary somewhat irregularly with frequency, a result which fits qualitatively with the fact that all dimensions of the specimens are comparable to the wave lengths of the sound (ANDERSON, 1950). In no instance have the results followed the Rayleigh scattering law (STRUTT, 1945) which applies when the dimensions of the scatterer are small compared with the wave length and would appear in Figs. 3, 5, 7, 8, 10 and 11 as a 12 db. per octave *increase* in target strength with frequency (Note : scattered intensity varies directly as the fourth power of the frequency). Indeed, target strengths of the squid, penaeid shrimp and scup show a general trend inverse to frequency ; higher values of scattering cross section may well be found at lower frequencies. Work is therefore now in progress to extend these measurements below 8 Kc. with the aim of extending them well into the Rayleigh region.

The results for the palemonid shrimp are not satisfactory, the signal-to-background-reverberation being entirely too low. However, these measurements serve to set an upper limit for scattering cross section for these shrimp.

ACKNOWLEDGMENTS

This work is a continuation of research on a problem suggested by Dr. J. B. HERSEY, under whose enthusiastic and helpful guidance the study has been conducted. The author also wishes to thank Mr. WILLARD DOW for his splendid advice in electronic problems and Mr. CHARLES WHEELER for providing the material (seine) and advice that led to the solution of the problem of pestiferous fish. Many other members of the Institution contributed materially to the success of this work, but a major portion of the assistance came from Mr. J. R. BRONK and Mr. D. SUPINO who worked with the author throughout the programme on the raft and in the laboratory.

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Contribution No. 730

INHIBITORY EFFECTS OF PHYTOPLANKTON UPON THE FEEDING OF *DAPHNIA MAGNA* WITH REFERENCE TO GROWTH, REPRODUCTION, AND SURVIVAL[1, 2]

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Introduction

It has been frequently observed, with respect to both the seasonal and geographical distribution of marine plankton populations, that the zooplankton is often scarce in waters rich with phytoplankton, and, conversely, that the animals may be most abundant in areas containing relatively few of the plant cells. This situation formerly appeared to be contradictory to the popular concept that the animals are largely dependent upon the phytoplankton for their food. In recent years, however, several explanations for this distributional pattern have been suggested, the most frequently quoted being the theories of "grazing" and "animal exclusion."

The theory of "grazing" proposed by Harvey *et al.* (1935) holds that the extensive feeding of the herbivorous zooplankton rapidly decimates the crop of phytoplankton living in the same waters with the animals, making unlikely the coexistence of large populations of both plants and animals. This grazing effect of a large population of the herbivores may presumably remove completely the standing crop of phytoplankton, and high concentrations of the latter can therefore develop only in the paucity or absence of the animals.

Hardy's theory of "animal exclusion" (Hardy and Gunther 1935; Hardy 1936), on the other hand, contends that dense populations of phytoplankton produce conditions which are unfavorable for the zooplankton, and that the latter consequently avoid or are excluded from these high concentrations of the algae. The physiological basis of the exclusion was not investigated by Hardy, but was believed to result from an inimical effect, presumably chemical in nature, of the phytoplankton upon the animals. Because this has never been clearly demonstrated in the laboratory or otherwise, Hardy's theory has lost much of its original impetus.

There is growing evidence, however, that dense populations of phytoplankton, in both marine and freshwater habitats, may create conditions which are inimical or actually lethal to a great variety of aquatic organisms. The literature dealing with this subject is too extensive to review here. The list of organisms which have been found to be adversely affected by phytoplankton includes numerous species of fish (Hardy 1936; Otterström and Steemann Nielsen 1939), shellfish (Bückmann 1934; Nightingale 1936; Loosanoff and Engle 1947; Korringa 1950), and barnacles (Allison and Cole 1934, 1935). Certain freshwater phytoplankters have been found to produce substances which inhibit their own growth (Pratt and Fong, 1940 and other papers; Storey 1943) and the growth of other species of algae (Rice 1954; Lefèvre *et al.*, 1951 and earlier papers).

In view of this evidence, the possibility that large populations of phytoplankton may, under certain conditions, create an unfavorable environment for the zooplankton, with which they are intimately associated, seems more than likely.

Lucus (1938, 1947, 1949) has presented a series of reviews concerning non-predatory relations between groups of organisms mediated by the production of external metabolites or "ectocrines" by the one group which produce a stimulatory or inhibitory effect upon the other. While his examples have been drawn from many fields of biology, Lucas has proposed a relationship of this type between plankton organisms as an explanation of Hardy's "exclusion" theory. In this connection, he states (Lucas 1947) "Here may be briefly considered the possible mediation of 'animal exclusion' in which it now seems reasonable to see the more or less passive avoidance of certain plant products (those typical of peak numbers) which in some instances may prove fatal if they cannot be avoided. . . . The widespread occurrence of antibiotics elsewhere makes highly probable the existence of such processes in the sea."

In considering the relations between phytoplankton and zooplankton populations, the freshwater environment has been largely neglected. Such studies as have been made have, in most cases, failed to demonstrate any correlation between the two groups, *e.g.* Pennak (1947). However, since

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[1] Portion of a thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Harvard University, Cambridge, Massachusetts.

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the numerically important species of phytoplankton and the herbivorous zooplankton belong to the same taxonomic groups and presumably occupy the same ecological niches in freshwater as in the sea, then it must be assumed, in the absence of evidence to the contrary, that the same relations exist between the plants and animals in both cases.

The experiments which will be described below concern the relations between the freshwater cladoceran, *Daphnia magna* and three species of planktonic algae in which there is presented evidence of a mechanism which provides a physiological basis for the concept of "animal exclusion."

The author expresses his sincere appreciation to Dr. G. L. Clarke for his helpful suggestions and critical analysis of this work. The investigation was carried out under the sponsorship of a U. S. Atomic Energy Commission predoctoral fellowship.

MATERIALS AND METHODS

Daphnia culture

Daphnia magna used in the experiments to be described below was obtained from stocks maintained at the Biological Laboratories of Harvard University. The animals were cultured in cement water tables measuring 66 x 24 inches in area which were kept filled to a depth of approximately 2 inches with constantly dripping tap water. The *Daphnia* lived in association with a population of snails, *Lymnaea palustris,* which was maintained by feeding regularly with lettuce. The *Daphnia* fed upon the fecal matter from the snails and its associated bacterial flora. This culture method proved to be extremely successful. Parthenogenetic reproduction occurred throughout the one-year period during which the experiments were in progress, eggs or young were always plentiful in mature animals, and no males or females with ephippia were ever observed.

Phytoplankton culture

Three species of algae were used for feeding *Daphnia* in the experimental work, the *Chlorophyta, Chlorella vulgaris* and *Scenedesmus quadricauda*, and the diatom, *Navicula pelliculosa.* The *Chlorella* was obtained in pure culture from Dr. W. T. Edmondson, and bacteria-free cultures were used for all experiments. *Scenedesmus,* which was isolated from a pond in Belmont, Mass., and *Navicula,* which was provided by Dr. Ruth Patrick, were maintained and used in unialgal but not pure cultures.

Algae were cultured in 10-liter batches in Pyrex jugs illuminated by water-cooled, immersed neon U-tubes and aerated with 5% CO_2, as described by Scott (1943). Smaller, 500-ml. flask cultures illuminated by a bank of daylight fluorescent lamps were also used. The same nutrient medium was used for growing all three species of algae and consisted of the following salts and concentrations:

Standard culture medium (Rice 1949)

$Ca(NO_3)_2 \cdot 4H_2O$	0.004%
$MgSO_4 \cdot 7H_2O$	0.002
KCl	0.004
$Na_2SiO_3 \cdot 9H_2O$	0.0025
$FeCl_3$	0.0001
KH_2PO_4	0.002
A-Z solution	0.100

"A-Z" solution is a mixture of trace elements described as "Solution A" by Hoagland and Snyder (1933). The growth of all algal cultures was determined from cell counts made at intervals of 2-3 days with a Levy hemacytometer.

Feeding experiments

Feeding experiments were conducted in a constant-temperature room maintained at 18-20° C. and were illuminated by an overhead fluorescent lamp providing 64 foot candles of light to the experimental vessel.

Daphnia were removed from their culture tank, washed in filtered pond water, and conditioned to the experimental temperature and illumination for 24 hours prior to each experiment.

Algae to be used in the experiments were centrifuged from their culture media and resuspended in filtered pond water to insure that a minimum of any substance, either metabolites of the algae or their mineral nutrients, would be carried over into the feeding experiment. This suspension of the algae was further diluted with filtered pond water to produce the desired concentration of cells as determined from hemacytometer counts.

Twenty-five *Daphnia* were then placed in a 100-ml. aliquot of the diluted algal suspension and allowed to feed for one hour. At the beginning and end of the one-hour period samples were withdrawn from the experimental vessel and the concentration of cells in each sample was determined from hemacytometer counts.

The filtering rate of the *Daphnia,* described for the purposes of these experiments as the number of ml. of water from which all cells have been removed per *Daphnia* per hour, was calculated by the same method as used by Gauld (1951) for marine copepods. Assuming the animals to be constant feeders, the concentration of cells in the water in which they are feeding will decrease exponentially according to the equation:

$$C_t = C_0 e^{-kt}$$

where C_t is the concentration at time t and C_0 is the initial concentration.

Filtering rate (F) may then be calculated from the equation:

$$F = vk$$

where v is the volume of water per *Daphnia*.

C_0 and C_t were determined by taking the mean of a series of 36-48 cell counts of 0.4 mm^3 hemacytometer fields of samples taken at the beginning and end of the experiment. Concentrations calculated in this manner gave a coefficient of variability ranging from 1% to 3%. Filtering rates determined in a series of identical feeding experiments gave a coefficient of variability of 10-20%.

Feeding experiments were conducted with all three species of algae using concentrations ranging from 0.1 to 0.6 million cells per milliliter.

Experiments were limited to a one-hour period to avoid the introduction of errors caused by the settling of cells during the feeding period. Controls containing algal suspensions with no *Daphnia* showed agreement between initial and final counts within the range of counting error for one-hour experiments, but showed a decrease after four hours often greater than the number of cells removed by the animals. Agitation or other methods of keeping the cells in suspension interfered with the normal activity of the animals and often stopped their feeding entirely.

EXPERIMENTS

A. The relation between the size of Daphnia and its feeding rate

Using the methods described above, four groups each of 25 *Daphnia* measuring respectively 1.5, 2.0, 2.5, and 3.0 mm. in length were fed *Chlorella*. In each experiment the same initial concentration of 0.20 million *Chlorella* per ml. was employed. Following each experiment, the *Daphnia* were dried for 24 hours at 60° C. and weighed.

On the basis of three experiments with each of the four size groups the mean number of *Chlorella* consumed per hour per mg. dry weight of *Daphnia* was calculated for animals of each size.

Food consumption per mg. dry weight plotted against the size of the *Daphnia*, also expressed in mg. dry weight, clearly indicates a straight line relationship, with *Chlorella* consumption an inverse function of size. (Fig. 1). From the straight line drawn through the four points by the method of least squares a curve was constructed showing the relation between size and food consumption per *Daphnia* (Fig. 1). This curve shows that maximum food consumption occurs in animals with a dry weight of 0.11-0.12 mg. (2.7-2.8 mm. in length).

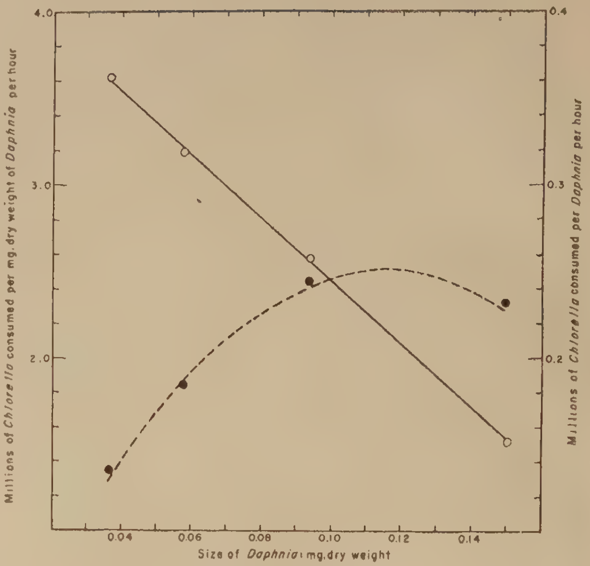

FIG. 1. Relation between the size of *Daphnia* and its feeding rate. *Chlorella* consumed per mg. dry weight of *Daphnia*-◎-·; *Chorella* consumed per *Daphnia* --●--.

It is also obvious that feeding rate in different-sized animals is much less variable when expressed per *Daphnia* rather than per unit of weight. Consequently, filtering rates in the following experiments have been calculated on that basis. Furthermore, experimental animals have been limited to a size range of 0.095-0.135 mg. dry weight (2.5-2.9 mm. length), within which variations in feeding rate due to size could be neglected.

B. Filtering rates of Daphnia feeding upon growing Chlorella

In a series of 86 one-hour feeding experiments, *Daphnia* were fed *Chlorella* from cultures which were in their log phase of growth. *Daphnia* used for this series were starved for 24 hours prior to the experiments and their intestinal tracts were completely empty except for a small plug of feces at the end of the gut. From five to ten experiments were made at each of 12 concentrations of *Chlorella* ranging from 0.05 to 0.60 million cells per ml. at intervals of approximately 0.05 million cells per ml. Following each experiment the filtering rate and the average of the initial and final concentration of *Chlorella* were calculated. Figure 2 shows the relationship between filtering rate and *Chlorella* concentration, each point representing the mean filtering rate and the mean average concentration of *Chlorella* of the five to ten experiments in which the *Daphnia* were fed approximately the same concentration of cells. It is at once obvious that there is an inverse relationship between filtering rate and the concentration of food, with the former decreasing as the latter in-

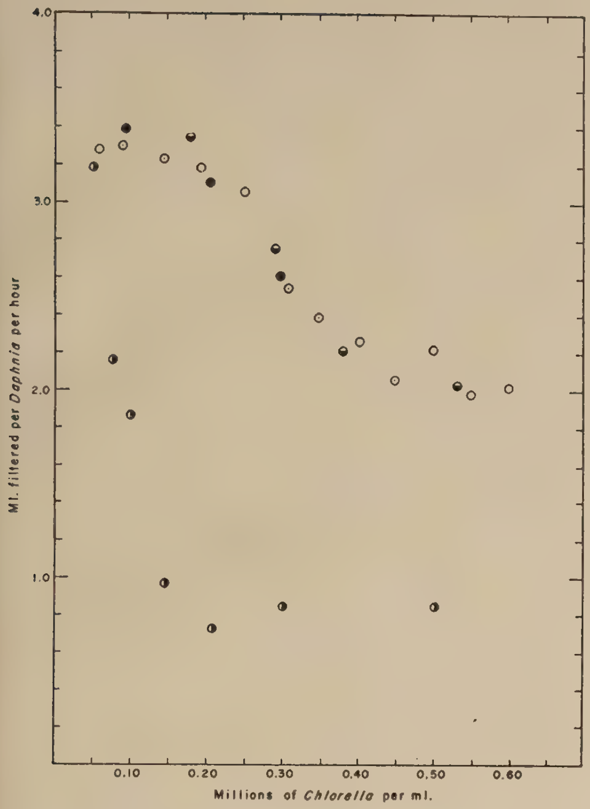

FIG. 2. Filtering rates of *Daphnia* feeding upon growing *Chlorella.* Starved *Daphnia* ◎ ; *Daphnia* fed detritus and bacteria prior to experiments ● ; starved *Daphnia* in media conditioned with growing *Chlorella* prior to experiments ◒ ; *Daphnia* fed growing *Chlorella* for 12 hours prior to experiments ◑ .

creases. This relationship is apparent within the entire range of the *Chlorella* concentrations which were used, but is most obvious at the intermediate concentrations of 0.2-0.5 million cells per ml.

An obvious explanation for this behavior is that the starved *Daphnia* decreased their feeding effort as they filled up with the algae. The higher the concentration of cells in which they are placed, the more rapidly they should be able to do this, and the lower would be the resulting hourly filtering rate.

To test this theory, three feeding experiments were conducted at *Chlorella* concentrations of approximately 0.1, 0.2, and 0.3 million cells per ml., using *Daphnia* which were conditioned to the experimental conditions for 24 hours in water taken from their culture tanks rather than in filtered pond water. These animals, in contrast to those used in the preceding experiments, had their intestinal tracts completely full of a black mass of food matter at the beginning of the experiments. These experiments were repeated twice using the same three concentrations of *Chlorella* each time, and the means were taken as before. The results indicate that the well-fed *Daphnia* filter at essentially the same rate as the starved animals feeding upon the same concentrations of cells (Fig. 2).

It may be concluded, therefore, that the amount of food, in itself, in the intestinal tracts of the *Daphnia* was not the factor responsible for the decrease in the filtering rates of animals feeding in progressively higher concentrations of *Chlorella.* Apparently, then, this effect resulted from some characteristic of the algae themselves.

Pratt and Fong (1940) demonstrated that *Chlorella vulgaris* produces and releases into its external medium a substance which inhibits its own growth. Later studies (Pratt *et al.* 1944) disclosed that this substance, named chlorellin by its discoverers, is antibiotic against gram-positive and gram-negative bacteria.

In view of this work, it appeared likely that the observed depression of the filtering rate of *Daphnia* might be mediated by the antibiotic, chlorellin, acting upon the animals either in solution in the water in which they feed, or within the *Daphnia* through its release from ingested cells.

The following series of experiments was designed to investigate whether chlorellin in solution in the water in which *Daphnia* are feeding could account for the depression of the filtering rate as observed in the preceding experiments. A culture of *Chlorella* in its log phase of growth was centrifuged and the cells resuspended in filtered pond water producing a concentration of 0.478 million cells per ml. After a period of 48 hours, during which the suspension was illuminated and agitated, the cells were removed by filtration. To this "conditioned" water, *Chlorella* and *Daphnia* were then added in the same manner as described above for the preceding experiments, and the filtering rate of the animals was measured as before. Initial concentrations of *Chlorella* were approximately 0.2, 0.3, 0.4, and 0.5 million cells per ml. and four to five experiments were performed at each of these concentrations. The mean filtering rate of these animals plotted against *Chlorella* concentration shows no significant difference from that of animals feeding upon the same concentrations of the algae in "unconditioned" water (Fig. 2).

In the series of experiments in which "unconditioned" water was used, there was a period of just one hour, the duration of the experiment, during which substances could have diffused from the algae into the *Daphnia's* surrounding medium. Since a relatively high concentration of *Chlorella* suspended in the water for an additional 48 hours did not further depress the filtering rate of the animals, the inhibition of feeding observed in these experiments apparently did not result from the accumulation of chlorellin or similar substances from the algae in the water.

A further possibility exists, however, that the inhibitory products of the algae produce their effect upon being released from ingested cells and assimilated by the *Daphnia*. The results of the experiments which were described above can be explained quite satisfactorily on the basis of such a theory.

If it may be assumed that the starved *Daphnia* were feeding at a constant "uninhibited" rate at the onset of the experiments, then this rate will decrease during the one-hour period as the animals ingest *Chlorella* cells and assimilate their inhibitory products. Thus the calculated filtering rate represents an average for the one-hour feeding period. The higher the concentration of *Chlorella* in the water at the beginning of the experiment, the greater will be the rates of ingestion of cells and assimilation of their inhibitory products, and the lower will be the average filtering rate.

It was noted above that at *Chlorella* concentrations between 0.05 and 0.25 million cells per ml. the depression of the filtering rate with increasing cell concentrations was very slight. Microscopic examination of *Daphnia* after feeding for one hour upon *Chlorella* within this range of concentrations disclosed the presence of relatively few cells in their intestinal tract.

In the process of feeding, *Daphnia* collects the filtered food particles in a ventral groove at the base of its thoracic appendages, whence the food is passed forward to the mouth and into the intestinal tract. Therefore, an appreciable number of cells must be filtered before any of them reach the absorptive part of the intestine, and in *Daphnia* feeding upon low concentrations of food organisms this may require a considerable period of time.

It would seem likely, therefore, that the *Daphnia* which were feeding upon *Chlorella* at concentrations below 0.25 million per ml. did not assimilate enough of the inhibitory substance to decrease their filtering rate in the course of the one-hour experiment.

Daphnia feeding upon *Chlorella* at concentrations exceeding 0.5 million cells per ml., on the other hand, were observed to fill completely their intestinal tracts with green cells within the course of the experiments, and these animals defecated green masses of apparently undigested algae for the remainder of the feeding period. With such high concentrations of the algae in the external medium of *Daphnia*, the cells appear to pass through the intestine so rapidly that efficiency of digestion is greatly reduced. It follows that the efficiency of assimilation of the inhibitory products of the algae is similarly reduced, and that the higher the concentration of the algae in the water, the lower that efficiency will be. This is believed to be the explanation of the fact that, with increasing concentrations of *Chlorella* above 0.5 million cells per ml., further decrease in the filtering rate of *Daphnia* is very small.

Daphnia which have been feeding continuously, or for long periods of time, upon *Chlorella* at any given concentration would be expected to feed at some constant rate. This rate should be considerably lower than that calculated in the preceding experiments for *Daphnia* feeding upon the same concentration of *Chlorella* for just one hour, where the filtering rate, as determined, represented a rate which was decreasing throughout most or all of the experimental period. An attempt has been made in the following series of experiments to measure the filtering rates of *Daphnia* which had been feeding upon various concentrations of *Chlorella* for periods of 12 hours prior to the experiments.

Groups of 25 *Daphnia* were placed in two-liter suspensions of log-phase *Chlorella* in filtered pond water at seven different concentrations of cells ranging from 0.05 to 0.50 million cells per ml. Every three hours the animals were transferred to a fresh suspension of the algae so that they were unable to lower the concentration in any case by more than 10%. The animals were allowed to feed in these suspensions of algae for a period of 12 hours. Following this, the *Daphnia* were transferred to small experimental vessels containing 100-ml. suspensions of the same concentrations of *Chlorella* upon which the animals had been previously feeding, and their filtering rates were determined as before for an additional one-hour period.

The mean filtering rate for three experiments conducted at each concentration of the algae was, in every case, considerably lower than that of starved *Daphnia* which had fed upon the same concentrations of *Chlorella* for just one hour (Fig. 2).

Above concentrations of 0.15 million cells per ml. the filtering rates appear to be rather constant, ranging from 0.72 to 0.96 ml. per *Daphnia* per hour. It was also observed that after animals had fed upon *Chlorella* at or above this concentration for 12 hours, their intestinal tracts were completely full of green cells. As mentioned above this situation apparently results in a minimum, constant filtering rate.

The *Daphnia* feeding upon 0.05 million *Chlorella* per ml. for 13 hours (12 hours' conditioning plus the experimental period) filtered at essentially the same rate as the starved animals which fed upon the same concentration of the algae for just one hour. It was postulated above that this represents the maximum, uninhibited filtering rate of the animals. It appears, therefore, that they were unable in 13 hours to consume enough algae at that concentration to be affected by their inhibitory products. At *Chlorella* concentrations between 0.05 and 0.15 million cells per ml. intermediate filtering rates were observed.

Whether or not an equilibrium had actually been reached by 12 hours was not determined. Presumably, however, there is a concentration of cells below which *Daphnia* are unable to keep their intestinal tracts filled with the algae no matter how long they feed, and another concentration below which continually feeding *Daphnia* can never consume sufficient *Chlorella* to be affected by the inhibitory products of the algae. Within the range determined by these two concentrations, the filtering rates of *Daphnia* feeding upon *Chlorella* under natural conditions would appear to be determined by the concentration of the algae in the water.

C. The filtering rates of Daphnia feeding upon senescent Chlorella

Studies by Pratt, Oneto, and Pratt (1945) revealed that the production of the antibiotic, chlorellin, is related to the physiological condition of the *Chlorella*. In cultures where the cells have a high division rate and the population is increasing exponentially, little or no chlorellin is released into the water, while senescent, static populations of the algae were found to produce the substance at maximum rates.

Care was taken in the experiments described in Section *B* to use only *Chlorella* from cultures which were growing exponentially. If the depression of the filtering rate of *Daphnia* feeding upon increasing concentrations of this actively growing *Chlorella* was due to the assimilation of chlorellin by the animals, then this inhibition should be more pronounced in the case of *Daphnia* feeding upon more slowly dividing algae. It may be noted in this connection that feeding rates reported in Section *A* are considerably lower than those observed in *Daphnia* feeding upon the same concentration of log phase *Chlorella* (cf. Figs. 1 and 2). Unfortunately data are not available concerning the growth phase of the *Chlorella* used in the former series of experiments. However, the relatively low filtering rate of the animals is suggestive of an increased inhibition possibly resulting from a more slowly dividing population of algae with a higher chlorellin concentration. To investigate this matter further, a series of experiments was performed similar to those reported in Section *B* with the exception that senescent, non-dividing *Chlorella* were used.

In experiments in which starved *Daphnia* were fed increasing concentrations of senescent *Chlorella* suspended in filtered pond water, the filtering rate was much lower at any concentration than that of animals feeding upon the corresponding concentration of log-phase *Chlorella* (Fig. 3).

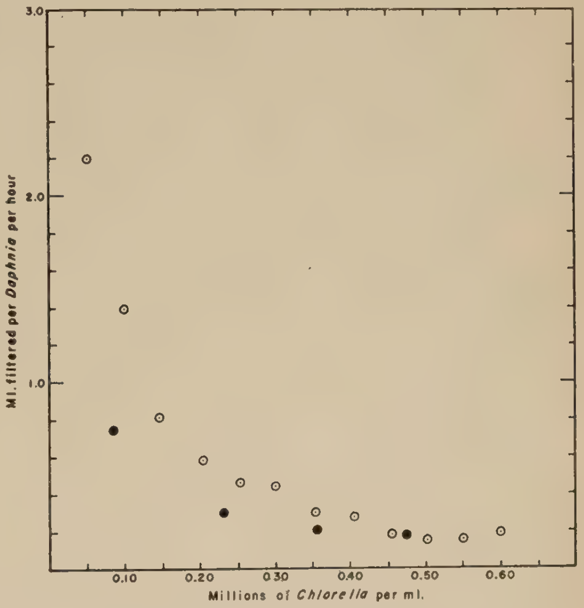

FIG. 3. Filtering rates of *Daphnia* feeding upon senescent *Chlorella*. Starved *Daphnia* ◎; Starved *Daphnia* in media conditioned with senescent *Chlorella* prior to experiments ●.

The same decrease in filtering rate with increasing cell concentrations of the senescent *Chlorella* occurs as in the case of *Daphnia* feeding upon the actively growing algae. However, it is noteworthy in this case that the *Daphnia* removed from the water approximately the same number of cells in one hour regardless of the concentration, in contrast to the animals feeding upon growing *Chlorella* where, despite a decreasing filtering rate, the *Daphnia* consumed increasingly larger amounts of *Chlorella* as the concentration of cells in the water increased (Table I). This trend is most obvious at *Chlorella* concentrations below 0.45 million cells per ml. and is somewhat obscured at higher concentrations because of the fact that error in estimating cell concentrations increases with the concentration.

TABLE I. *The numbers of log-phase and senescent* Chlorella *filtered by* Daphnia *feeding upon various concentrations of the algae.*

Approximate mean conc. of *Chlcrella.* (cells/ml. x 10^6)	Log-phase *Chlreolla* filtered. (cells x 10^6/hr./*Daphnia*)	Senescent *Chlorella* filtered. (cells x 10^6/hr./*Daphnia*)
0.05	0.20	0.11
0.10	0.30	0.14
0.15	0.48	0.12
0.20	0.62	0.12
0.25	0.77	0.12
0.30	0.78	0.13
0.35	0.83	0.11
0.40	0.91	0.11
0.45	0.92	0.08
0.50	1.10	0.07
0.55	1.03	0.08
0.60	1.20	0.11

The fact that *Daphnia* feeding upon the senescent *Chlorella* appear to consume approximately the same amounts of the algae regardless of its concentration in the water suggests that the animals cease feeding entirely after the ingestion of a certain number of these cells. This recalls the earlier comment that a given number of cells must be filtered from the water before any of them reach the intestinal tract.

To determine whether chlorellin released into the water from the senescent algae could affect the filtering rate of *Daphnia,* filtered pond water was conditioned with a suspension of 0.5 million non-dividing *Chlorella* for 48 hours. The algae were then removed by filtration and senescent *Chlorella* and *Daphnia* were added to the conditioned water and the filtering rates of the animals measured as before. Results of four to six experiments at each of four concentrations of the algae show that a further inhibition of the filtering rate was produced by the conditioned water in the experiments in which *Daphnia* were fed senescent *Chlorella* at concentrations below 0.3 million cells per ml. (Fig. 3). Above this concentration there was no appreciable difference between the experiments in which conditioned and unconditioned water were used. Presumably at the higher concentrations of the algae sufficient cells are consumed within the first few minutes of the experiment to cause the animals to cease feeding, and the effect of the chlorellin in solution is masked.

In a third series of experiments with senescent *Chlorella, Daphnia* were placed in various concentrations of the algae for 12 hours prior to the measurement of their filtering rates for an additional hour, in the same manner as in the similar series in which growing *Chlorella* was used. After 12 hours of exposure to the senescent *Chlorella,* none of the *Daphnia* showed any signs of having fed during the ensuing one hour experiment. Even at concentrations as low as 0.05 million cells per ml. there was no significant difference between cell counts at the beginning and end of the feeding period. Examination of the *Daphnia* showed no trace of the algae in their intestinal tracts.

D. Feeding experiments with Navicula and Scenedesmus

Feeding experiments similar to those described above were performed with starved *Daphnia* feeding for periods of one hour upon the diatom *Navicula pelliculosa* and the chlorophyte *Scenedesmus quadricauda.* The animals were fed both rapidly growing and senescent cells of both species at various concentrations. *Scenedesmus* is a colonial form which occurs as single cells or, more commonly, as two- or four-celled coenobia. The filtering rates of *Daphnia* feeding upon this species were calculated on the basis of particles rather than single cells consumed.

The results of experiments with these two species of algae were similar in all respects to those in which the animals were fed *Chlorella* with the exception that the magnitude of the variations of the filtering rate was not so great under the different conditions which were studied. (Figs. 4, 5.) If the observed depression of the filtering rate of *Daphnia* feeding upon *Chlorella* resulted from the inhibitory product of the algae, chlorellin, then it must follow that both *Navicula* and *Scenedesmus* produce substances of a similar nature

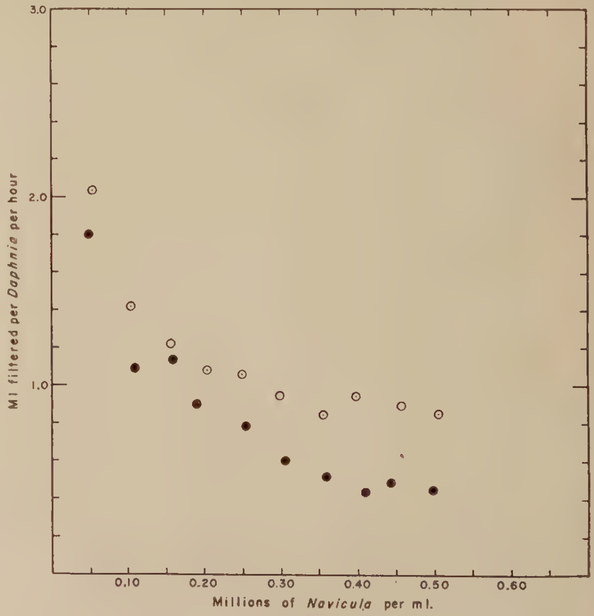

FIG. 4. Filtering rates of starved *Daphnia* feeding upon growing *Navicula* ◎ and senescent *Navicula* ● .

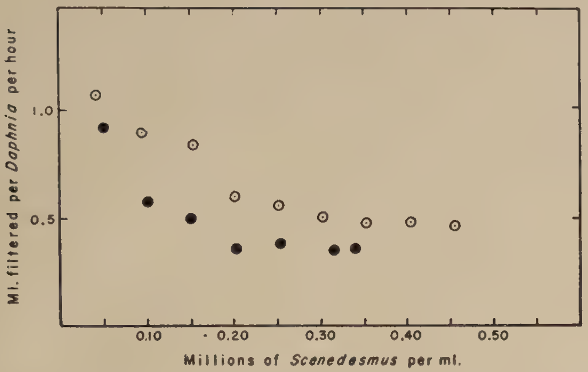

FIG. 5. Filtering rates of starved *Daphnia* feeding upon growing *Scenedesmus* ◎ and senescent *Scenedesmus* ●.

which also act as inhibitors upon the feeding process of the cladoceran.

At any given concentration of algae in the same physiological condition, *Daphnia* were observed to feed most rapidly upon *Chlorella* and at the lowest rate upon *Scenedesmus*. This appears to be related to the size of the algae. Average cell volumes of *Chlorella* and *Navicula* were 3.5 μ^3 and 9.2 μ^3 respectively, and the average volume of the *Scenedesmus* coenobia was 25.5 μ^3.

The possibility was considered that the animals filtered the larger species of algae less efficiently than the smaller *Chlorella* cells. However, in a series of six experiments in which *Daphnia* were fed mixed cultures containing equal numbers of *Scenedesmus* and *Chlorella*, the same number of each species was consumed in one hour (Table II).

TABLE II. *The rates of consumption of* Chlorella *and* Scenedesmus *by* Daphnia *feeding upon mixed cultures of the algae.*

Mean concentration of algae. (cells or colonies/ml. x 10^6)		Cells or colonies consumed/ *Daphnia*/hour x 10^6	
Chlorella	*Scenedesmus*	*Chlorella*	*Scenedesmus*
.175	.174	.22	.25
.179	.169	.24	.24
.178	.180	.24	.25
.181	.183	.26	.25
.170	.184	.24	.22
.159	.170	.27	.26

Since it has already been demonstrated that the amount of food consumed by the *Daphnia* does not, in itself, affect the filtering rate of the animals, it must be assumed that the different algae here considered produce different amounts of the inhibitory substances per cell, a likely possibility in view of their difference in size, or that these substances differ in their effect upon the *Daphnia*.

E. The effects of the age of Chlorella upon the growth, reproduction, and survival of Daphnia

In view of the marked difference between the rates at which *Daphnia* feed upon rapidly growing and senescent populations of *Chlorella*, the following experiment was designed to demonstrate the longer-term effects which the algae in these two conditions might have upon the growth, reproduction, and longevity of *Daphnia*.

Ten cultures were inoculated each with 25 *Daphnia* which were born the day the experiment began. These animals, all from the same clone, averaged 1.0 mm. in length at the start of the experiment. The cultures consisted of finger bowls containing 200 ml. of filtered pond water. Cultures 1-5 were fed *Chlorella* in its log phase of growth and cultures 6-10 were fed senescent *Chlorella*. All cultures were fed at the rate of 50 million cells per day for the first six days and 100 million cells per day thereafter. Every day prior to feeding, the water in each culture was replaced with fresh, filtered pond water, and any animals which had died or had been born during the previous 24 hours were removed. Every three days 10 animals were removed at random from each of the two groups of cultures and measured.

The results of the experiment are summarized in Table III showing the average number of young and the average number of deaths per culture per day and the average size of the 10 animals measured every three days for the two groups of cultures.

The animals which were fed log-phase *Chlorella* grew rapidly throughout the 13 day experiment and by the 12th day had reached a high rate of reproduction. No animals died in this group.

TABLE III. *The growth, reproduction, and longevity of* Daphnia *which were fed actively growing and senescent* Chlorella.

Days	*Daphnia* fed growing *Chlorella*			*Daphnia* fed senescent *Chlorella*		
	Av. size mm.	Young per culture	Deaths per culture	Av. size mm.	Young per culture	Deaths per culture
1......	1.0	0	0	1.0	0	0
2......	...	0	0	...	0	0
3......	...	0	0	...	0	0
4......	1.6	0	0	1.3	0	0
5......	...	0	0	...	0	0
6......	...	0	0	...	0	0
7......	2.2	0.4	0	1.4	0	0
8......	...	2.0	0	...	0	0
9......	...	8.0	0	...	0	0
10......	2.6	17.6	0	1.5	0	0.6
11......	...	16.0	0	...	0	5.6
12......	...	45.6	0	...	0	9.2
13......	2.9	43.4	0	—*	0	9.6

*All animals dead

Those which were fed senescent *Chlorella* grew very slowly with no evidence of ecdysis during the experiment. No young were produced nor were eggs observed in any individual in this group. These animals were completely unpigmented in contrast to the reddish-brown color of the *Daphnia* which were fed growing *Chlorella,* and they were relatively inactive, spending most of their time resting on the bottom of the finger bowls. They began to die on the 10th day and were all dead by the 13th day, thereby ending the experiment.

Discussion

The experiments which have been described in this report represent, to the author's knowledge, the first extensive study of the feeding rate of a freshwater, filter-feeding zooplankton organism. The only work with which it may be compared, therefore, is that of investigators who have studied the feeding habits of marine zooplankton.

Clarke and Fuller (1936), in the first preliminary work on this subject, found that the filtering rate of *Calanus finmarchicus* feeding upon carmine particles averaged, in six experiments, 5.6 ml. of water filtered per animal per 24 hours. In an extension of that work, Fuller (1937) fed *Calanus* upon the diatom, *Nitzschia closterium,* using a range of concentrations from 0.002 to 0.41 million cells per ml. From a series of 12 feeding experiments within that range, he observed an average filtering rate of 1.08 ml. per *Calanus* per 24 hours.

Lucas (1936), also using *Nitzschia* as a food organism, conducted feeding experiments with the copepod, *Eurytemora hirundoides,* and the mysid, *Neomysis vulgaris.* His experiments, which involved a wide range of concentrations of the diatom, showed mean filtering rates of 2.9 ml. per copepod and 0.011 ml. per mysid per 24 hours, but the results of both series showed a coefficient of variability of over 75%.

Fuller and Clarke calculated, from the daily food requirements of *Calanus* as given by Marshall, Nicholls, and Orr (1935), that stage V *Calanus* would require a minimum filtering rate of 72 ml. per 24 hours in order to subsist upon the various components of the phytoplankton and nannoplankton occurring in Vineyard Sound at a time when the copepod was abundant there. This figure is at considerable variance with the observed filtering rates of *Calanus* discussed above.

Harvey (1937), however, observed that while *Calanus* fed upon *Nitzschia* at a rate of only 4.56 ml. per animal per 24 hours, the copepod fed upon the larger diatoms, *Lauderia borialis* and *Ditylum brightwelli,* at rates of 48-96 ml. and 168-240 ml. per animal per 24 hours respectively.

Fuller interpreted this to mean that the smaller *Nitzschia* passed through the filtering mechanism of the copepod, and, in consequence, the filtering process was relatively inefficient with particles of that size. This seems rather doubtful in view of the success of Raymond and Gross (1942) in culturing *Calanus* upon flagellates 1-2 μ in diameter, organisms an order of magnitude smaller than *Nitzschia.*

Furthermore, Gauld (1951), who has probably made the most extensive study of the feeding of marine zooplankton, observed that the filtering rate of stage V *Calanus* feeding upon a marine *Chlamydomonas* averaged 64 ml. at 12.5° C. and 95 ml. at 17° C. per animal per 24 hours. These figures show a reasonable agreement with those of Harvey for *Calanus* feeding upon the larger diatoms. However, Gauld points out that the *Chlamydomonas* used in his work was considerably smaller than the *Nitzschia closterium* forma *minutissima* used by both Fuller and Harvey. Hence differences in the size of the food organisms can hardly account for the observed variability in the filtering rate of the copepod.

In none of the work which has been described above was there observed any tendency for the animals to decrease their filtering rates in increasing concentrations of the food organisms. As a result, the opinion now appears to be widely accepted that these grazers filter at a constant rate, at a given temperature, which is unaffected by the concentration or other characteristics of the food in the water (Lucas 1936; Fuller 1936; Fleming 1939; Harvey 1942; Riley 1946, 1947.)

However, not only were the experimental results reported by the individual workers in every case extremely variable, but filtering rates of the same animal feeding upon different species of food organisms, as reported by different authors, were in some cases not of the same order of magnitude. Since fundamentally the same methods were used in every case, these variations are hardly consistent with the concept of a fixed, constant, filtering rate.

The feeding experiments with *Daphnia* have demonstrated that, within a limited range, the concentration of algae in the water may have a pronounced effect upon the filtering rate of that animal. Of even greater importance, however, is the physiological condition, or population age, of the phytoplankton in its effect upon the feeding of the cladoceran. The latter appears to be a factor which has hitherto not been considered in this respect.

The combination of the two factors, concentration and age of the phytoplankton population, was found to produce a range in the filtering rate of *Daphnia* from a maximum of 81 ml. per animal per 24 hours to a value approaching or equalling zero. It is perhaps significant that this range closely approximates that observed by Fuller and Gauld for stage V *Calanus,* an animal similar in size to *Daphnia.*

In view of the similarity of the inhibitory effects, insofar as they were studied, of the three species of algae upon *Daphnia,* and the widespread occurrence of inhibitory or toxic effects of phytoplankton upon a great variety of other aquatic organisms, as reported elsewhere, it is not unreasonable to propose a relationship of this type between natural populations of phytoplankton and zooplankton filter feeders. Here may be reconsidered briefly the frequently reported inverse correlation between the abundance of phytoplankton and zooplankton which was discussed in the opening of this paper with a re-evaluation of Harvey's grazing theory and Hardy's concept of "animal exclusion."

The ideal food for *Daphnia* appears to consist of young, actively dividing populations of phytoplankton. In that state, the algae are fed upon by the animals with great rapidity. With high concentrations of the cells in the water, they are consumed at rates which are greatly in excess of the *Daphnia's* nutritional requirements, and a large fraction of the ingested algae pass through the animal's intestine unassimilated.

A similar situation was reported by Harvey *et al.* (1935) in the English Channel during 1935 and 1936. There, the spring diatom blooms for those years were observed to disappear suddenly, although nutrients and other conditions appeared to be favorable for the continued growth of the plants. The simultaneous increase in the numbers of large copepods, and the observation of quantities of the fecal pellets of the animals colored green with chlorophyll led these workers to the conclusion that the phytoplankton crop was depleted by the extensive grazing of the herbivores.

In *Daphnia* this situation may obtain only so long as the phytoplankton cells are actively dividing. If, in a natural situation, conditions become favorable for an eruptive growth of phytoplankton, the latter may grow at a higher rate than they can be removed by grazing. The algal population will then no longer be limited by the animals, but will increase until its supply of nutrients becomes exhausted. As the population peak is approached, inhibitory substances accumulate in the algal cells, and they presumably no longer represent a suitable food for the grazers.

The experimental *Daphnia,* confined to the same water mass as the senescent phytoplankton, ceased feeding and eventually died. In an open body of water, it is more likely that actively swimming animals would be able to avoid these concentrations of toxic phytoplankton. This, in essence, is the situation proposed by Hardy in his theory of "animal exclusion."

SUMMARY

1. The filtering rate of *Daphnia magna,* defined as the volume of water swept free of food per animal per unit of time, was determined from one-hour feeding experiments using as food organisms the Chlorophyta *Chlorella vulgaris* and *Scenedesmus quadricauda* and the diatom *Navicula pelliculosa.*

2. Filtering rate per unit of weight of *Daphnia* is an inverse function of the animal's size. Under given conditions, the maximum filtering rate occurs in animals approximately 2.7 mm. in length.

3. Starved *Daphnia* feed upon *Chlorella* at the same rate as animals which had previously fed upon bacteria and detritus and whose intestines were filled with such material at the onset of the experiments.

4. The filtering rate of *Daphnia* is inhibited by substances produced by the three species of algae tested. The inhibitory product of *Chlorella* appears to be identical to the previously described antibiotic, chlorellin. The inhibition is mediated partially by substances which diffuse from the cells and accumulate in the water. A much more pronounced effect appears to be produced by the release of the inhibitory products from ingested cells within the animal.

5. The minimum inhibition is produced by actively growing algae from cultures which are in their log phase of growth. The maximum effect is produced by senescent, non-dividing algae.

6. In the one-hour feeding experiments in which starved or bacteria-and-detritus-fed *Daphnia* were fed varying concentrations of the algae, the filtering rate was inversely proportional to the concentration of cells in the water. The explanation was proposed that the filtering rate is proportional to the rate of ingestion of cells and assimilation of their inhibitory products, both of which in these experiments were dependent upon the concentration of cells in the water.

7. When *Daphnia* were fed actively growing *Chlorella* for 12 hours prior to the feeding experiments, the filtering rate for the ensuing one-hour period was much lower than that of starved

Daphnia at any given concentration of the algae. At *Chlorella* concentrations below 0.15 million cells per ml. the filtering rate was inversely proportional to the concentration of the algae. At concentrations above that value the filtering rate was constant.

8. No sign of feeding could be detected in *Daphnia* which had been exposed to suspensions of senescent, non-dividing *Chlorella* for periods of 12 hours prior to the feeding experiments.

9. Within the size range represented by *Chlorella* (3.6 μ^3) and *Scenedesmus* (25.5 μ^3) *Daphnia* shows no selectivity in its feeding, removing cells of both species at the same rate from mixed populations of these algae.

10. *Daphnia* cultured upon actively growing *Chlorella* cells grew rapidly and, upon reaching maturity, maintained a high rate of reproduction. *Daphnia* cultured upon senescent, non-dividing *Chlorella* grew very slowly, failed to reproduce, and died after 11-13 days.

11. The possibility and ecological significance were discussed of a widespread occurrence in nature of the inhibition of zooplankton filter feeders by senescent populations of phytoplankton. This relationship was proposed as a physiological basis of Hardy's theory of "animal exclusion."

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Contribution No. 734

(*Reprinted from Nature, Vol.* 173, *p.* 1048, *May* 29, 1954.)

Bursting of Bubbles at an Air–Water Interface*

In a recent communication[1], we presented a series of high-speed photographs of bursting bubbles at an air–water interface. These photographs demonstrate the manner in which small airborne droplets evolve from the vertical water jet which forms upon collapse of the bubble cavity. These studies were carried out as a contribution to the understanding of the role of bursting bubbles in the production of atmospheric sea-salt nuclei[2]. It was stated that our study was confined to bubbles of 0·2–0·02 cm. diameter. In this region the jet mechanism appears to be the only one responsible for the production of airborne nuclei. We did not imply that the production of airborne salt was entirely via the jet mechanism. For example, in a study of foam patches, it may turn out that the production of droplets is predominantly from the collapse of the bubble film[3].

The more recent communication of Knelman *et al.*[4] states "that two separate mechanisms are involved in the bursting of a bubble—one producing a cloud of droplets of diameter about 60 microns, and the other a few comparatively large drops of diameter approximately 1 mm.". Inasmuch as the authors give no reference to the size of bubble used in their work, the implication is that these two mechanisms can be applied to all cases of bubble bursting. Intuitively this is not plausible and experimentally it can be shown not to hold true. An examination of the photograph in this communication[4] indicates that the bubble is probably greater than 0·3 cm. and possibly as large as 0·6 cm. in diameter. This was determined by noting the degree to which the bubble penetrated the surface film while at rest at the surface. The larger a bubble, the larger is the ratio of the buoyant to the surface tension forces; these forces being dependent upon volume and surface respectively. This ratio can be used to provide a measure of the tendency of the bubble to rise above the surface. The bubbles studied in our work, as compared to those illustrated in the communication by Knelman *et al.*, had a much greater percentage of their volume beneath the surface. It is thus reasonable to conclude that the investigation was confined to bubbles greater than 0·3 cm. in diameter; this is further confirmed by the statement that the jet produces droplets of approximately 1 mm.

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* Contribution No. 734 from Woods Hole Oceanographic Institution.

diameter. This certainly would require bubbles greater than $0{\cdot}3$ cm. If their conclusion regarding the two separate mechanisms was based on observations of such large bubbles it would scarcely seem correct to infer that phenomena associated with these bubbles should also be found in the bursting of much smaller bubbles.

I have observed the bursting of bubbles of less than 50 microns diameter and find the jet mechanism producing droplets of 2–20 microns diameter; but can see no evidence as to any cloud produced by the bursting of a protuberance on the bubble film. If such a cloud is present, its droplets must be far less than 1 micron in diameter.

Thus we must be very cautious before we can accept any single mechanism to explain the production of airborne droplets from the bursting of bubbles. It is possible that the mechanisms proposed by Knelman *et al.* are important in the production of droplets from a collection of large bubbles in the form of a foam patch. In any event, it would be useful if Knelman and his co-workers could present more detailed information in regard to the extent of the size-range of bubbles used in their investigation. Their high-speed photography has demonstrated the existence of an interesting and possibly important phenomenon. A knowledge of the range of bubble-sizes encompassed by this mechanism has sufficient interest to warrant further investigation.

D. C. BLANCHARD

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts.

March 17.

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Report for the year 1954

THE
WOODS HOLE OCEANOGRAPHIC INSTITUTION

REPORT FOR THE YEAR
1954

1955

Laboratory of Oceanography of the Office of Naval Research

Woods Hole, Massachusetts

The Laboratory of Oceanography stands on the water-front at Woods Hole, adjacent to the Woods Hole Oceanographic Institution. This facility is operated by the Institution under contract with the Office of Naval Research. The building was dedicated by high ranking officers of the U. S. Navy on June 21, 1954.

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III. RESEARCH STAFF

(As of December 31, 1954)

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Bostwick H. Ketchum, Senior Oceanographer.

Alfred C. Redfield, Professor of Physiology, Harvard University; Senior Oceanographer.

Scientists

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Dean F. Bumpus, Oceanographer.

Andrew F. Bunker, Meteorologist.

George L. Clarke, Associate Professor of Zoology, Harvard University; Marine Biologist.

Willard Dow, Electronics Engineer.

Frederick C. Fuglister, Physical Oceanographer.

John B. Hersey, Physical Oceanographer.

Joanne S. Malkus, Meteorologist.

Willem V. R. Malkus, Physical Oceanographer.

Charles B. Officer, Jr., Geophysicist.

Francis A. Richards, Chemical Oceanographer.

William S. Richardson, Physical Chemist.

Carl-G. Rossby, Director, Institute of Meteorology, University of Stockholm; Meteorologist.

Harold E. Sawyer, Research Engineer.

Per L. Scholander, Physiologist.

William C. Schroeder, Associate Curator of Fishes, Museum of Comparative Zoology, Harvard University; Ichthyologist.

Mary Sears, Planktonologist.

Henry C. Stetson, Research Oceanographer and Alexander Agassiz Fellow in Oceanography, Museum of Comparative Zoology, Harvard University; Submarine Geologist.

Henry M. Stommel, Physical Oceanographer.

Harry J. Turner, Jr., Marine Biologist.

Allyn C. Vine, Physical Oceanographer.

William S. von Arx, Physicial Oceanographer.

Alfred H. Woodcock, Oceanographer.

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Earl W. Barrett, Research Associate in Meteorology.

Duncan C. Blanchard, Research Associate in Meteorology.

Robert H. Brockhurst, Research Associate in Physics.

John G. Bruce, Jr., Research Associate in Physics.

Elizabeth T. Bunce, Research Associate in Physics.

Joseph Chase, Research Associate in Meteorology.

Harlow G. Farmer, Jr., Research Associate in Hydraulics.

David H. Frantz, Jr., Research Associate in Engineering.

Henry R. Johnson, Research Associate in Underwater Acoustics.

John W. Kanwisher, Research Associate in Biophysics.

Sydney T. Knott, Jr., Research Associate in Engineering.

Robert A. Lufburrow, Research Associate in Physical Oceanography.

Wilbur Marks, Research Associate in Physical Oceanography.

Frank J. Mather III, Research Associate in Oceanography.

William G. Metcalf, Research Associate in Physical Oceanography.

Arthur R. Miller, Research Associate in Physical Oceanography.

David M. Owen, Research Associate in Underwater Photography.

F. Claude Ronne, Research Associate in Photography.

John H. Ryther, Research Associate in Marine Biology.

Karl E. Schleicher, Research Associate in Physics.

Herbert Small, Research Associate in Electronics.

Allard P. Spencer, Research Associate in Engineering.

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Levie Van Dam, Research Associate in Physiology.

Robert G. Walden, Research Associate in Electronics.

Geoffrey G. Whitney, Jr., Research Associate in Physical Oceanography.

L. Valentine Worthington, Research Associate in Physical Oceanography.

Ralph F. Wyrick, Research Associate in Underwater Acoustics.

John W. Zeigler, Research Associate in Marine Geology.

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Jerome Namias, Associate in Meteorology.

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Roy L. Rather, Jr., Associate in Underwater Acoustics.

Gordon A. Riley, Associate Professor of Marine Biology, Yale University; Associate in Marine Physiology.

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IV. DIRECTOR'S REPORT

Introduction

THERE are so many interesting and varied features pertaining to research in the field of oceanography, that when one sits down to prepare a report of the year's activities of an Institution such as this one, a careful sense of evaluation has to be exercised. Speaking with the experience of only a few years at Woods Hole, but having been intimately associated with it for many, I have noted that the emphasis in research moves about. At one time, for example, the central point of interest focuses on problems dealing with the circulation of the surface layers of the ocean and efforts to derive a predication formula. Another time it is the interface between the air and sea with its processes of exchange that beckons. And so on.

The past year has witnessed more than normal interest and effort directed towards problems associated with the over-turn and renewal of the deeper water-masses of the ocean. A recurring question has been, what is the rate of exchange between the surface and the depths? Due to the inaccessability of abyssal waters, and the creeping rate of motion which has been assumed for these masses, little or no quantitative data have been obtainable. This is not a problem inherent to Woods Hole alone — it faces oceanographers throughout the world. Obviously too, this problem of the little known deeper circulation is one which will be with us for many years to come. It has such great implications, moreover, that it challenges one of oceanography's major research-engineering efforts.

One of the new investigations related to the above question is in the field of radio activity, which an atomic age has accelerated. A form which this inquiry has already taken is the gathering of information on the feasibility of using the depths of the ocean as a safe disposal dump for atomic wastes.

As in other fields of research, instrumentation plays an important role in the work both in the laboratory and in the ships at sea. During the past few years, it seems as if more than the ordinary effort has been made to advance the mechanical techniques. For example, we can point to two devices developed and being tested, one an improved method of determining seawater salinity by means of an electrical resistance bridge, the other an experimental instrument recovery buoy. A vigorous development program of oceanographic equipment and techniques paralleling the research, especially as these new tools assist to reduce or replace ship-time at sea, is an avowed policy of the Institution.

Among the firsts, therefore, this year we list:

(*a*) Field observations and statistical studies of the secular decrease of oxygen over the whole western North Atlantic at depths greater than 2500 meters.

(*b*) The summer's Labrador Expedition of the Institution's physiological group.

(*c*) The cooperative meteorological expedition to the Hawaiian Islands to investigate the processes which produce rain from warm marine clouds.

(*d*) Evaluation of the oxygen and the C^{14} methods, respectively, of determining photosynthetic activity in the ocean.

(*e*) The establishment of a laboratory of radio-isotope techniques as applied to oceanographic problems.

The Institution's sources of income this year have stemmed not only from its own endowment fund, but also, as in previous years, from the more substantial source of contracts with agencies of the Department of Defense, the National Science Foundation, and others. This year, furthermore, marked the establishment of Corporation Membership in the Associates of the Woods Hole Oceanographic Institution, and what appears to be the inauguration of a significant financial support of our oceanographic research. More extended remarks on the activities of the Associates and their cooperation are contained in a subsequent section.

The largest gift to the Institution since its establishment twenty-four years ago was that of a sizable lot of water-front property in East Boston, Massachusetts, made possible through the generosity of the General Foods Corporation of New York.

The report of the year's work of the Research Staff follows from the Senior Scientists.

Research

So far as the circulation problem is concerned there have been several developments during the last year. Mr. F. C. Fuglister spent the spring months at La Jolla examining some of the extensive temperature surveys of Pacific Ocean areas. Not only did he bring to the Scripps Institution of Oceanography a new point of view based on our experience with the Gulf Stream, but also he was able to show in a very effective manner that the Pacific data could be so analyzed as to support his multiple current hypothesis. This was true not only of the Japanese temperature surveys in the western Pacific, but also of the many detailed surveys of the very contrasting area off the coast of California.

Mr. L. V. Worthington became interested in deep observations of dissolved oxygen after helping to secure such data last winter from the Brownson Deep. Acoustic transmission measurements in this area had indicated that there might be a rather sharp gradient of temperature and salinity at the contact between bottom water of South Atlantic origin which fills the bottom of the trench and the less dense North Atlantic deep water.

In comparing recent deep oxygen determinations with some secured about thirty years ago he discovered that below a depth of about 2,500 meters over the whole western North Atlantic basin new observations showed about 0.3 cc per liter less oxygen than was found by the early expeditions. Since the oxygen-depth curves are in close agreement above 2,500 meters there is little chance that the chemical analyses are at fault.

Mr. Worthington came to the conclusion that there had been no, or very little, production of sufficiently dense water in high latitudes of recent years to sink below 2,500 meters in the North Atlantic. Using the indicated rate of consumption of oxygen, namely, 0.3 cc per liter in thirty years, he then calculated the length of time since the deep water was saturated with oxygen. This turned out to be approximately 140 years, an age very different from that indicated by the published C^{14} determinations; namely, about 1,500 years. From the standpoint of those who have been studying ocean circulation the lower figure is very much more acceptable. Furthermore, the climatological record shows that during several years centering around 1810 abnormally cold winters and even cold summers prevailed. Thus the supposition is that only during a cold climatic maximum does surface water become sufficiently dense to sink in large enough quantity to influence widely conditions deep down in the ocean.

During May Mr. Worthington made a long cruise on the CARYN to secure additional deep oxygen observations to compare with the old surveys. During the autumn he also made a cruise to the Caribbean on the ATLANTIS. These newest data continue to support his belief that oxygen is being consumed faster than it is being replaced by sinking of surface water in high latitudes. It is interesting to note that, if his estimate of the rate of consumption is correct, it will only require about 1,000 years before all the oxygen below a depth of 2,500 meters is used up. If, indeed, the ocean only overturns completely during exceptionally cold periods, there are many other important implications. However, the whole concept is too new to warrant further speculation here.

Mr. Henry Stommel returned from Bermuda in April having secured a large number of days of successful measurements of wind drift from his free-floating, radio telemetering buoys. Since then he and Mr. Robert Walden through more careful antenna design have succeeded in greatly increasing the assured radio range. Mr. Harlow Farmer has been making some design studies of the buoy-case with the objective of gaining a more stable and more seaworthy platform. An important by-product of his prospective design is that there would be much less danger of a buoy damaging the propeller of a passing vessel. After these and other engineering studies have been completed we will be in good position to assess the capabilities of free-floating buoys in oceanographic research.

During the autumn Mr. Stommel, assisted by Mr. Sloat Hodgson, set out a cable off Bermuda with thermal elements at three depths, the objective being to record internal waves. Arrangements were also made with the Bermuda Biological Station to secure bi-monthly deep hydrographic stations in the vicinity of the cable's sensing elements. The installation has continued to function well.

Considerable progress has also been made in the design of a reliable release for submerged buoys. Mr. David Frantz has successfully recovered his buoy on a number of occasions and we are gaining considerable confidence in his system. Essentially the device, which consists of an airtight chamber containing automatic recording instruments and a radio transmitter, is anchored at any desired subsurface depth. Recovery is achieved at the end of the desired observational period by exploding from the collecting ship, a charge which frees the buoy to the sea surface where it sends out radio signals. The reception of these transmissions by a direction finder leads to recovery of the buoy and its record. Homing on the buoy after it has surfaced has been accomplished each time with ease. The next step is to extend considerably the effective life of the release which is only about six weeks. It seems probable that this can be done by using transistors and such work is now in progress.

In short, in the circulation problem we seem to be at last approaching the point where our vessels will have the help of a variety of different kinds of buoys capable of gaining continuous information over extended periods of time.

While studying at M. I. T. last winter Mr. W. S. von Arx was able to consult with a number of interested experts concerning his plans for larger model studies which will now become possible in the new hydraulics laboratory. He has received much encouragement that his 24-foot diameter flat basin will perform as planned, and during this summer a graduate student from M. I. T. has been making some tests of a 7-foot flat basin preparatory to the design of the large one, the base and container for which is located in the new hydrodynamics building. Means of heating the water in low latitudes, and cooling it in high latitudes, have been provided, so at least in a qualitative way we will soon gain some insight as to what happens in a rotating model when heating and cooling are combined with a wind-driven circulation.

Theoretical studies of the circulation problem also for the first time are beginning to include the idea that thermohaline factors can combine with wind effects to produce currents. Mr. Henry Stommel and Dr. Willem V. R. Malkus have been developing a mathematical model of the Gulf Stream which permits the current to call upon energy available to it in the Sargasso

Sea as the result of deep winter wind stirring. As a consequence of the recent series of lectures by Dr. Jule G. Charney there has been much fruitful discussion concerning the possibilities of achieving a substantial advance in theories that apply both to large-scale meteorological and oceanographic phenomena.

During spring and summer, Dr. Malkus also carried out successful Gulf Stream cruises in the CARYN using novel methods. Starting near Cape Hatteras he drifted downstream along the axis of the current observing the changes in the velocity-depth distribution as a function of time. As usual the Gulf Stream each time did the unexpected. After moving rapidly for about 500 miles the water mass which the CARYN was observing slowed down and came virtually to a stop. There seemed to be the end of one filament of the Gulf Stream after passing through several more or less developed meanders. The relatively short endurance of the CARYN then became critical, for they were not able to establish with certainty the manner in which the isotherms marking the inshore edge of the swift current which they had been following linked up with another filament of current that each time was located about 50 miles inshore. Thus we have one more piece of evidence that the Gulf Stream System, near the surface at least, is somewhat discontinuous in nature. The filaments of swift flow appear to overlap more or less like the shingles on a roof.

During August the ATLANTIS made two geological cruises. An exceptionally large number of graduate students in geology worked here this summer and these cruises were in part planned to give them as much experience as possible in different aspects of submarine geology. On the first cruise they explored the canyons on the Nova Scotian continental shelf, and on the second one they examined and sampled the new sea mounts south of Georges Bank and then headed south to the red clay area northeast of Bermuda with the hope of obtaining some long cores. However, as so often happens in summer the plans were largely thwarted by the need of dodging two hurricanes.

Mr. H. C. Stetson's studies of the changes in underwater topography off exposed beaches are continuing. Through the enthusiasm and ingenuity of a friend of his, a pressure recording device has been constructed. By dragging this along the bottom, underwater profiles can be obtained across the surf zone more quickly and more safely than when the soundings have to be taken from a dory.

Opportunity for some very practical work in the geology of the continental shelf has occurred recently. As a part of the design study for some offshore, permanent structures we were asked to examine a number of proposed sites. Dr. John M. Zeigler enthusiastically undertook responsibility for this work. By aqua-lung swimming it was quickly shown that

Cashes Ledge is a solid mass of granite. On the other hand, the shoal part of Browns Bank as seen by underwater photography is covered by a mixture of sand, gravel, and boulders of all sizes. Two areas on each of Georges Bank and Nantucket Shoals were sounded in detail. Here, nothing but sand was encountered on the surface of the bottom. Two difficult questions were then posed to us by the foundation engineers: How deep are the sands and how much do the shoals shift in position? To answer the first of these questions, corings have been made from a DeLong barge. At one site the sands were more than 120 feet thick. At each site that has been drilled, a 5-inch diameter pipe was left standing in the core hole and extending about 15 feet above the bottom to serve as a permanent marker. Buoys have been set out and therefore it will be possible during the months ahead to observe in detail the changes in the sand ridges.

Wave research has also been contributing much to this project and in turn will gain from it. During the times when the barge was jacked up out of the water, it served as a fixed platform for the calibration of our free-floating wave recorders. A year or more from now when the permanent towers are erected they can serve in many ways as oceanographic observatories.

The development phase of floating wave recorders has about been completed. The instruments now work well in moderate seas, but are not large enough to withstand storm conditions. We have worked out a promising design for a ship-borne wave recorder which we feel is superior for scientific purposes to a similar British instrument.

During early October arrangements were made by the Office of Naval Research to obtain the services of two planes equipped with excellent cameras. Under the leadership of Mr. Wilbur Marks many pairs of photographs of the sea surface were secured. The ATLANTIS served as the scale for the photogrammetric analysis. The contouring of the best pair of photographs showing seas up to about 12 feet in height has been carried out at the Hydrographic Office. About one-half square mile of the sea surface has thus been frozen for the analysis of wave spectra.

The increasing interest in ocean wave phenomena stems partly from the many new applications of wave prediction methods, partly from the increasing concern of ship designers in wave phenomena, and partly from the very great advances in wave theory that have taken place at New York University. Wave research is the one outstanding case in oceanography where theory has outstripped our observational abilities and we can take pride in the fact that in the months before his death Dr. H. R. Seiwell provided the foundations for these developments.

Mr. Marks has also been hard at work computing the energy spectra of small waves observed in Narragansett Bay last winter. The technique he is using continues to show great promise. If it turns out, as we believe it will, that small waves in a limited fetch resemble storm waves in their statistical characteristics, then many possibilities open up for interesting model studies.

During most of the winter the BEAR and the ATLANTIS were engaged in making acoustical and geophysical observations on a cruise to Puerto Rico. On the way south and also when returning, the vessels shot a refraction profile along the middle part of the continental shelf. Fifteen determinations of the depth to the basement were obtained. This is the first time that such observations have been made south of Cape Hatteras. It is clear from the measurements that the rock structure on which Cape Fear rests extends across the continental shelf underneath the sand deposits.

Dr. Charles B. Officer returned in April from a six month's visit to New Zealand under a Fulbright Fellowship. Using the available earthquake records, he made a highly successful study of the crustal structure of the southwest Pacific. While this is a rather complex region, he was able to distinguish between areas having an oceanic crust and those of a continental type. He was also able to show that a number of the islands, including New Zealand, have been built up with succeeding geologic time on an oceanic crust. They are not part of an extensive continent.

Dr. Officer received the prize for the best paper published in *Geophysics* in 1953, the title of which was "The Refraction Arrival in Water Covered Areas." He was also invited by the American Society of Exploration Geophysicists to give a series of lectures during the late autumn.

Following a suggestion of Mr. A. C. Vine, an examination was made of some "scattering layer" records secured by the BEAR south of Woods Hole. Dr. J. B. Hersey and Dr. R. H. Backus were able to show that the peak frequencies from the several different layers not only were different, but also that they increased in frequency as the layers descended in a manner roughly proportional to the first power of the depth. Since so sensitive a variation with depth suggests a highly compressible scatterer such as a gas bubble, on the basis of gas bubble theory they computed the diameter and volume of the corresponding gas bubbles at one atmosphere for the three most prominent frequency peaks. The range of sizes falls within those given for the swim bladders of common bathypelagic fishes. In the case of lantern fishes, known to be numerous in the area in question, particularly good agreement was found between the bubble size as computed from the acoustical measurements and actual measurements of the swim bladders themselves. While these results are a strong indication that most of the sound scattering in this area comes from the swim bladders of fish, this is by no means the only source of back scattering.

Steady improvement has been made in our ability to gain reliable measurements of the transport of heat, momentum, and water vapor in the turbulent layer of air over the ocean from the PBY plane. Encouraging confirmation of the accuracy of our instrumentation was received recently when the Johns Hopkins group distributed a report of their values of the shearing stress obtained during a joint operation but by a completely different method. Also in another joint operation when the plane was flown upwind past the meteorological tower at the Brookhaven National Laboratories there was again opportunity to compare data taken from a fixed platform with the measurements gained by the plane. The PBY appears to be the only type of plane with a sufficiently rigid wing structure to give adequate response to small-scale turbulence. Thus, this particular plane has become a carefully calibrated meteorological instrument and, as far as we know, it is unique.

Mr. Andrew Bunker is presently at work reducing the data on the above phenomena that he obtained last winter on flights over the Gulf of Mexico.

Dr. Joanne S. Malkus has been working on the 1953 cloud data from the Caribbean. With the help of Mr. Claude Ronne and Dr. William S. Richardson some laboratory experiments have been in progress in which Schlieren photography is being used to observe convective bubbles formed in air and in water over a uniformly heated metal plate.

Dr. Malkus and her husband left for England in September to spend the winter at the Imperial College of London. Dr. Willem Malkus has also been spending several days each week at the National Institute of Oceanography.

During July Dr. Herbert Riehl of the University of Chicago was at Woods Hole in order to discuss the role of cumulus convection in the maintenance of the basic circulation of the trade winds.

Mr. Alfred H. Woodcock organized and lead a major cooperative expedition to the Hawaiian Islands during the fall months in order to study the processes that produce rain from warm clouds. He arranged for the collaboration of Australian, Swedish, and American experts on various phases of cloud physics. The aim was to make a grand assault on the problems of warm clouds, taking advantage of the very favorable situations and facilities existing at Hawaii.

Mr. Duncan Blanchard has been studying in the laboratory the electrical charge on the minute droplets which are thrown into the air when air bubbles of various sizes break through a salt-water surface.

All of these various projects and others that have not been mentioned are considerably more intimately related than is likely to be made clear by such a summary as has been given above. The exchange of energy between the sea surface and the atmosphere is a central theme which is being studied in many different ways, yet each investigator is well aware of the results and plans of his colleagues. In the same way the work on the circulation problem is being well integrated. The laboratory has not become so large that people with common interests cannot frequently consult so as to pool skills and techniques. The most difficult part of the program to merge with the others is the work in underwater acoustics. Dr. Richard Backus is trying to make acoustical techniques more readily available to biologists. The geologists through Dr. John Zeigler are no longer mystified by what goes on inside a recording echo sounder. However, the fact that so much of the literature of underwater acoustics is classified makes it a field to which physical oceanographers are somewhat reluctant to contribute much time. At the same time those having an appropriate background in physics or electrical engineering find it difficult to take the time to learn oceanography. It is hoped that through the new laboratory a better merging of acoustics and physical oceanography will gradually result.

The most comprehensive problem in oceanography is to determine the relationships on which the distribution and abundance of life in the sea depend. This problem requires a knowledge not only of the distribution of the many kinds of animals and plants in the sea and of their physiological and biochemical activities and requirements, but also an understanding of the circulation of the water and its chemistry, since these determine the quality of the environment in which marine organisms live. Marine ecology consequently is a synthesis of physical, chemical, geological, and biological information aimed at giving an intelligible picture of the sea as a system productive of living matter.

The great advantage which the biologists of the Institution enjoy is close association with experts in the physical fields which contribute to this problem. The complexity of the question has made it useful to use relatively confined bodies of water as "test tubes" in which general relations can be worked out under some control. Since the hydrography of such bays and estuaries is undeveloped, it has been necessary for the biologist to turn hydrographer and develop the physical information basic to his more general problem.

Since all animal life produced in the sea depends upon the microscopic plants which transform solar energy into the chemical energy required for growth, the program of the microbiology and chemistry group includes studies of the interrelationships between: (1) growth and photosynthesis of the phytoplankton, (2) the oxygen and carbon dioxide exchanges associated with photosynthesis, (3) the chemical nutrients (nitrogen, phosphorus, silica, etc.) in the water required for growth, and (4) the bacterial processes which ultimately decompose the organic matter formed and return the chemicals to solution to be used again in the cycle. In the field studies, the hydrography must always be considered, since different parts of the cycle may be widely separated if the currents carry the surface water, where photosynthesis takes place, in a different direction or speed from the deeper waters, where much of the decomposition must occur. Some aspects of the problem are more readily studied in the laboratory; others in local confined areas which can be revisited frequently.

Each member of the group has his own specialty, but all are contributing towards the basic understanding of this broad problem. During 1954 the following investigations have been made.

Professor E. Steemann Nielsen of the Royal Farmaceutiske Hojskole, Copenhagen, Denmark, visited the Institution for a period of six months. During his visit he continued his studies of photosynthesis under laboratory conditions. His visit was very stimulating to our group which is using his Carbon-14 method for evaluating the productivity of the phytoplankton in the sea.

The Carbon-14 method of Steeman Nielsen for determining productivity has produced an estimate, for areas such as the Sargasso Sea, which is much less than the estimate derived from the oxygen method, used extensively by Dr. Riley of our staff. During his visit Steemann Nielsen performed experiments which indicate that the bacterial respiration may be inhibited by an antibiotic produced in the light as a by-product of photosynthesis. This would yield unusually high results by the oxygen method, but would not affect the Carbon-14 method.

In a carefully controlled laboratory experiment, Dr. Ryther has shown that the difference between Riley's and Steemann Nielsen's results may be related to the deficiency of nutrients (phosphorus and nitrogen) in such areas as the Sargasso Sea, and may reflect the physiological condition of the phytoplankton which grow there. This explanation suggests that the respiration of the nutrient deficient plants themselves may be nearly equal to their photosynthesis so that all of the organic matter formed is immediately respired. The oxygen method measures both the respired material as well as that remaining in the cell as new growth, whereas the Carbon-14 method measures only the latter, and assumes that a small proportion is respired. Further work is necessary and is planned to resolve the contradiction in these two valuable methods.

Dr. Ketchum prepared a review of the "Nutrition of Phytoplankton" which has appeared in (the 1954 issue of) *Annual Reviews of Plant Physiology*. The results of ecological studies and of laboratory studies were considered in order to show how each field could profit by a closer understanding of the problems in the other. Dr. Richards has written a review of the distribution of oxygen in the oceans which will appear as a chapter in the "Treatise on Marine Ecology and Paleoecology" to be published by the Ecology Sub-Committee of the Division of Geology and Geography of the National Research Council.

Dr. Richards and Dr. Redfield have completed an analysis of the distribution of oxygen in the Gulf Stream system. It was found that part of the Gulf Stream water, which apparently originates in the Caribbean, contains much lower concentrations of oxygen than water of the same density in the Sargasso Sea. This difference provides a method of tracing and differentiating the source of some of the water of the Gulf Stream.

In a paper published in 1937 Redfield, Smith and Ketchum showed that analysis of the total phosphorus content of seawater, supplemented by the conventional measurement of inorganic phosphate, could be used to untangle the essential features of the phosphorus cycle. The technical difficulties in the determination of total phosphorus have been largely eliminated, and a large number of samples can now be analyzed in a routine way. The samples can be obtained on any hydrographic cruise without the necessity of a chemist on board. The perfection of this technique should make it possible to increase greatly our knowledge of the distribution of phosphorus. A start has been made in obtaining data on the distribution of total phosphorus in the western North Atlantic. Samples have been analyzed for the International Ice Patrol in the belief that phosphorus may aid in characterizing different water masses. Samples have also been collected on several cruises to other parts of the North Atlantic.

The analysis of the distribution of nutrients in the tropical Atlantic is being continued on data obtained during the "Trade Winds" cruise of 1952. The determination of total phosphorus for about 3000 samples collected during this cruise has been completed. About 95% of the surface waters of the Equatorial Atlantic contain appreciable quantities of organic phosphorus most of which is present as dissolved organic compounds. A small fraction of the total phosphorus is found in the bodies of plants and animals. The deeper waters, however, contain an insignificant amount of the organic phosphorus. These observations emphasize the fact that most of the biological cycle is completed in the upper 1000 meters and that little of the organic matter formed in the surface waters can be expected to reach the bottom at greater depths.

Mr. Vaccaro has examined the distribution of oxidized forms of nitrogen in the samples collected on the Trade Winds cruise, and has correlated their distribution with the oxygen content of the water. Mr. Vacarro was aboard ATLANTIS during the first part of cruise 196, when he conducted studies of productivity and collected samples for the analysis of the concentration of nutrients in the waters of the continental shelf south of Cape Hatteras. Mr. Foster conducted similar investigations on CARYN cruise 72 and ATLANTIS cruise 208.

Papers on the hydrography, phosphorus cycle, zooplankton and phytoplankton of Great Pond, a small estuary near Falmouth, have been prepared by Dr. John Barlow and Mr. E. M. Hulburt. A further study of the seasonal changes in the biological population and in the distribution of nutrients and oxygen in this estuary are being conducted by Conover, Foster, and Creitz. Great Pond is becoming a very useful "Test Tube" for testing principles, which grows in value as its ecology becomes better understood. Such studies, on small bodies of water which can be revisited frequently, increase our knowledge of the interrelationships among the various factors which influence and control the basic productivity of the oceans.

Another case in point is Lake Maracaibo in Venezuela to which a party from the Institution made a second visit in March, under contract with the Creole Petroleum Corporation. This is reputed to be one of the most productive bodies of water in the world, and has provided a wonderful opportunity for studying the hydrographic and climatological factors on which organic production depends. The Climatological Laboratory of Johns Hopkins University is collaborating in this study.

As an outgrowth of interest in Lake Maracaibo, the ATLANTIS made a hydrographic and biochemical survey of the Gulf of Venezuela in December. On the way there a hydrographic station was occupied in the Cariaco Trench, a deep depression in the continental shelf off the Venezuelan coast. The water in this great hole was found to be devoid of oxygen, and loaded with hydrogen sulfide from depths of 400 meters to the bottom at 1200 meters. The conditions are similar to those found in the Black Sea, and in many poorly circulated fjords. It is the first case where such conditions have been found to exist in a depression in the bottom of the open ocean. Further chemical studies of the water in the trench will be made during the next visit of the ATLANTIS to the Caribbean.

A follow-up survey of Great South Bay and Moriches Bay, Long Island, was made in July at the request of the Towns of Islip and Brookhaven. This provided opportunity to extend the studies made in previous years on the effects of the opening and closing of Moriches Inlet on the conditions in these polluted embayments.

One of the benefits of having the new Oceanographic Laboratory is that it enables the Institution to undertake new ventures for which recently there has been no room in its building. The first of these ventures is the establishment of a laboratory equipped for the application of radioactive isotype techniques to oceanographic problems, such as the use of Carbon-14 by Dr. Ryther for measuring the assimilation of carbon by phytoplankton. Now a properly equipped laboratory is being installed for Dr. Vaughan T. Bowen, who comes to the Institution from the Brookhaven National Laboratory, as geochemist.

Dr. Bowen's objectives are two-fold; first to study the distribution in present day Atlantic seawater of as many of the long-lived fission products as can be detected, and second to apply radiochemical techniques to problems in the biogeochemistry of substances present in such small amounts that they cannot be dealt with effectively by other methods of analysis.

Dr. Thomas Sugihara of Clarke University spent the summer with Dr. Bowen attempting to develop methods for measuring the presence of Strontium-90, by way of its radioactive daughter, Yttrium-90. Dr. Sugihara has continued this study since returning to Clarke University and will return to Woods Hole next summer. Dr. Bowen is examining the chemistry and biological activity of the rare earths in the ocean. Progress in this problem awaits the development of effective methods of extracting the materials and concentrating them in measurable quantities.

Mr. Thomas Goreau of the University College of the West Indies was associated with Dr. Bowen during the early winter, learning radioactive techniques, and has returned to Jamaica to apply the use of radioactive calcium to the deposition of calcium in coral reefs.

During the first week of August a conference was held in Woods Hole between representatives of the principal agencies concerned with the disposal of radioactive wastes, as produced in large quantities in the industrial use of atomic energy, to consider problems which would arise from disposal of large quantities of waste at sea, and to determine what research should be done in this connection.

A related development is the study of the distribution of deuterium, an isotope in hydrogen, in the sea. This has grown out of an association with the U. S. Geological Survey formed two years ago through Dr. Daniel R. Norton. Dr. Irving Friedman, an associate of Norton's in the Survey, has developed methods for the estimation of the deuterium in natural waters. The Institution has supplied him with seawater samples for his preliminary studies and is undertaking to secure material for a world-wide coverage of the oceans. This is a study which has great promise, since the deuterium determinations enable one to trace the movements of water itself in its cycle of evaporation from the sea surface, its movement through the atmosphere, and its return to the sea as runoff from the land.

Dr. Scholander has made excellent progress in his studies of the remarkable mechanism by which fish are able to secrete gas into their swim bladders against the great pressures existing in the deep sea. An examination of the equilibrium between oxygen and the blood of deep sea fish has pretty thoroughly disposed of the hypothesis generally held that this activity can be explained by the effects of acidity upon the properties of hemoglobin (the Bohr and Root effects) and indicate that some unknown biochemical or physical mechanism working within the swim bladder gland is forcing oxygen into the bladder. These studies have also demonstrated the remarkable fact that the swim bladder gland can secrete the inert gas argon and nitrogen with the same facility with which it handles the more active oxygen molecule.

Dr. Kanwisher has commenced a study of the ability of marine organisms to withstand being frozen. He finds that a number of species which live between tide lines recover even after a large part of their water has been converted into ice. This seems to be an adaptation developed particularly in the intertidal species and is a matter of interest because of the increasing use of freezing techniques in surgery.

The physiological group took a leading part in an expedition to Labrador during the summer. The expedition was sponsored by the Arctic Institute of North America and was led by Commander D. C. Nutt of Dartmouth College. A portable laboratory was established on Hebron Fjord where Dr. Scholander was able to continue studies made in Baffin Land in 1953 on the ability of fish to live at temperatures so low that their blood might be expected to freeze. Dr. Kanwisher extended his investigation of the ability of marine animals and plants to survive freezing to organisms naturally exposed to much more severe conditions than are found at Woods Hole. Dr. Scholander also brought back the first analyses of the gases entrapped in iceberg ice, which he believes may provide a record of the composition of the atmosphere in past ages.

In addition to the physiological contingent from Woods Hole scientists from Rutgers, Michigan, Chicago, Yale, McGill, and Dartmouth conducted studies on the microbiology, marine algae, plankton, lichens and fish of the region while Commander Nutt continued his hydrographic studies of the Hebron Fjord and Nain areas.

Mr. William C. Schroeder made two cruises during the summer to explore the fish fauna of the continental slope. These expeditions bring to completion the present phase of these studies and he is now preparing a report on his findings. Commercial fishermen are now exploiting profitably the concentration of lobsters which he discovered in deep waters, being able to catch up to 5,000 pounds of lobsters in the course of two day's fishing. A commercial enterprise is now investigating the possibility of canning the large crabs found in this area.

Under the joint authorship of Henry B. Bigelow and William C. Schroeder there appeared during the year two notable contributions to our knowledge of fish. These are a paper on "Deepwater Elasmobranchs and Chimaeroids from the Northwestern Atlantic Slope," published by the Museum of Comparative Zoology at Harvard and a monograph describing the skates, rays, and chimaeras which forms Part II of a series of memoirs on "Fishes of the Western North Atlantic" being issued by the Sears Foundation for Marine Research at Yale.

The migrations of the large pelagic fish, such as tuna, are a mystery of interest to scientists and sportsmen alike. Some success has been had recently in tagging relatively small tuna which can be taken alive into a boat, but marking really big tuna without injury to man and fish is another matter. Mr. Frank J. Mather III has recently devised a miniature harpoon which may be used to plant a tag in a large fish when it has been brought alongside, after which the fish may be released in the hope it will be caught again at some distant point. Mr. Mather attended a recent tuna-fishing tournament at Bimini, where this device attracted the attention of sport-fishermen who have volunteered to help in his investigation.

The Institution continues to enjoy a contract with the Commonwealth of Massachusetts for research on shellfish. This year Mr. Harry J. Turner's report to the State contains a very valuable review of the extensive studies on shellfish which have been made by state and federal agencies during the last ten years.

Mr. Turner has conducted a tagging experiment in connection with the rock crab fishery in Boston Harbor which indicates that at least 22 percent of the crab population is caught each season. He is now investigating the factors which may effect the growth of the quahaug, *Venus mercenaria*, in salt water ponds, to see if it is practical to raise these clams in controlled enclosures.

Dr. Mary Sears published this year an account of the ecology of Pisco Bay, Peru, a region of interest in connection with the occurrence of El Niño and its effect on the guano industry. Dr. Sears is now serving as the American Editor of *Deep-Sea Research* a recently established international journal of oceanography. Her skillful editorship is helping to provide an outlet of the highest quality for the publication of oceanographic papers.

Dr. George L. Clarke, who pioneered during the pre-war period on measurements of the penetration of light into the sea and on studies of the related diurnal migrations of zooplankton has developed an extra sensitive submarine photometer. It is believed that this instrument will measure the very low light intensity present at the depths occupied by the scattering layer and will thus contribute to understanding the vertical migration of the organisms believed to be responsible for this phenomenon, which is of such great interest to physical oceanographers and biologists alike. We welcome Dr. Clarke's return to the investigation of a subject to which he has contributed so successfully in the past. Dr. Clarke published during the year a text book "Elements of Ecology" which will be influential in the education of the next generation of marine biologists.

Publications

Sixty scientific papers bearing contribution numbers have been published in 1954.

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Worthington, L. V. Three detailed cross-sections of the Gulf Stream. *Tellus*, 6(2):116–123, 11 text figs.	694
Richards, F. A., and A. C. Redfield. A correlation between the oxygen content of seawater and the organic content of marine sediments. *Deep-Sea Res.*, 1(4):279–281, 2 text figs.	695
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Hersey, J. B. Acoustic instrumentation as a tool in oceanography. In: Oceanographic Instrumentation. *Nat. Res. Counc. Publ.* No. 309:101–122, 7 text figs.	697
Arons, A. B. Underwater explosion shock wave parameters at large distances from the charge. *J. Acoust. Soc. Amer.*, 26(3):343–346, 3 text figs.	698
Scholander, P. F., and L. Van Dam. Secretion of gases against high pressures in the swimbladder of deep sea fishes. 1. Oxygen dissociation in blood. *Biol. Bull.*, 107(2):247–259, 4 text figs.	699
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Montgomery, R. B. Convection of heat. *Arch. Meteorol., Geophys. u. Bioklim.*, A, 7:125–132.	701
Mather, F. J., III. Northerly occurrences of warm water fishes in the western Atlantic. *Copeia*, 1954(4):292–293.	702
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Worthington, L. V. A preliminary note on the time scale in North Atlantic circulation. *Deep-Sea Res.*, 1(4):244–251, 5 text figs.	717
Clarke, A. H., Jr. Some mollusks from the continental slope of northeastern North America. *Breviora*, No. 40:11 pp.	722
Newton, C. W. Frontogenesis and frontolysis as a three-dimensional process. *J. Meteorol.*, 11(6):449–461, 14 text figs.	723
Smith, P. E. Further measurements of the sound scattering properties of several marine organisms. *Deep-Sea Res.*, 2(1):71–79, 12 text figs.	728
Ryther, J. H. Inhibitory effects of phytoplankton upon the feeding of *Daphnia magna* with reference to growth, reproduction and survival. *Ecology*, 35(4):522–533	730
Blanchard, D. C. Bursting of bubbles at an air-water interface. *Nature*, 173:1048	734

In addition to the strictly scientific and technical papers which have appeared during the year by members of the Research Staff, there have been a few semi-popular scientific articles on oceanographic subjects contributed to periodicals as follows:

Malkus, Joanne S., Trade Wind Clouds — *Scientific American*, Nov. 1953, Vol. 189, No. 5, pp. 31–35, figs. in text, 6.

The Institution published three issues of a pamphlet called Oceanus for the benefit of the Associates of the Woods Hole Oceanographic Institution. This modest little magazine contains an assortment of news and reports on oceanography and the main developments of the Institution's research.

Other publications of the Institution in 1954 include two illustrated brochures, one entitled, "Your Stake in the Last Frontier," and the other, "Perpetuating Your Love for the Sea." The purpose of the former is to interest industrial corporations in extending support to the basic oceanographic research of the Institution, and the latter is a step toward increasing the capital endowment of the Institution.

Vessels and Airplanes

The Institution's fleet of research vessels and airplanes kept active in 1954.

Ship operations for the year began in mid-January with the departure of ATLANTIS and BEAR for an extended southern cruise which lasted until the first of April. In spite of rather heavy weather, the southbound leg witnessed a full hydrographic schedule under the chief scientiest, Mr. Bumpus. The research operations in Puerto Rican waters and return to Woods Hole, was under Dr. Hersey's supervision. Sound transmission observations in company with the Hudson Laboratory's Ship ALLEGHENY, and a submarine, provided a full program.

ATLANTIS parted company with BEAR at Woods Hole to proceed to Munroe's Yard, Boston, for a six weeks overhaul, the major items being a complete engine refit and the replacement of a fractured tail shaft. Again it was apparent that age makes for more extensive yard work than with a younger ship.

ATLANTIS engaged in an extremely busy summer schedule consisting of trips to the Gulf Stream and the Nova Scotian Shelf, while later she journeyed to Bermuda and carried out a bathymetrical survey of Kelvin Bank. The year-end witnessed ATLANTIS' return from a voyage to mid-Atlantic, to Barbados, and the Caribbean, under chief scientist Worthington. During the year she put in 213 days at sea.

CARYN was recommissioned in mid-May from which date until late fall she was kept pretty much underway. Several of the Staff used her for their particular projects, the largest one being a six weeks hydrographic cruise, three hundred miles southeast of Bermuda to St. Thomas and return. Mr. Worthington, chief scientist, reported an efficiently operating ship which confirmed the belief of several at the Institution that CARYN, for certain kinds of oceanographic field work, is quite useful. She operates at approximately one-third less cost than ATLANTIS.

BEAR, following its winter cruise with ATLANTIS plied on a weekly program out of Woods Hole for Dr. Hersey and Mr. Vine testing experimental equipment and conducting acoustical operations south of Martha's Vineyard. The installation of a Sperry gyroscopic compass was a feature, which after considerable adjustments, is now believed to be a reliable instrument. The latter part of the year witnessed a rather extensive overhaul and general refit which the BEAR had not had for a long time.

ASTERIAS, our smaller 40-foot craft was employed throughout the year for harbor and coastwise trips ranging from Jamestown, Rhode Island to Gloucester, Mass.

This year marked the second one in which an airplane on loan from the

Navy was operated for oceanographic research. The PBY-6A-46683 made several over-water flights on missions which included cloud physics and turbulence studies for the meteorological group; charting of the inner edge of the Gulf Stream off the Atlantic seaboard for the hydrographic group, and photographing the changing shore line in the beach study work. A cooperative mission of the Institution, and the U. S. Coast Guard's Ice Patrol, took the airplane to Argentia, Newfoundland.

To find an airplane which fits the needs of both the oceanographers and the meteorologists is difficult, the former desiring a relatively slow-speed craft, the latter needing a rather fast airplane with large fuel capacity to cover expansive sea areas.

A Stinson Voyager airplane was received in February from the Civil Aeronautics Authority via the Navy, it having been declared surplus equipment and offered to the Institution for whatever research purposes we might find it useful. While not as adaptable to most of the oceanographic work as the larger airplane, it has become employed in limited meteorological work and for occasional utility purposes.

As all of those who were living in coastal New England August 31 and September 9, 1954 vividly recall, visitations by hurricanes caused great damage to marine property. Fortunately the ATLANTIS was in Bermuda during the passage of Hurricane Carol, and the CARYN successfully rode it out moored to the Institution's pier at Woods Hole. None of the smaller craft of the Institution was damaged. On two other occasions, however, the two larger vessels had to seek a more protected harbor being dispatched from Woods Hole to Boston, thus causing considerable disruption in research operations and consequent loss of valuable time.

The desirability of reproducing the older units of our fleet, particularly the ATLANTIS, with ships designed for modern oceanographic operations, is a task which continues to engage our attention.

A detailed summary of the year's operations of the Institution's fleet is to be found in the Appendix.

Plant

The physical holdings of the Institution received an unusual increment during March through a donation by the General Foods Corporation of 361,000 square feet of land and four buildings located at New Street, East Boston, Mass., and assessed for tax purposes in the sum of $276,000. This figure was considered excessive due to the present state of disrepair of the buildings and the abandonment and non-use of the property since the General Foods Corporation had removed its activities to another site a year or more ago.

Although the Institution had no practical use of the property itself in the immediate future, acceptance was based upon subsequent lease or sale, if the interests of the Institution could be best served by such action. At the close of the year an appeal to the City of Boston tax authorities had been filed, and the property appraised and reparceled for sale or lease. It is hoped that financial benefits will eventually be realized on this real estate holding.

Mention has already been made of the hurricanes of 1954. The Institution's pier witnessed the water level rising at the height of Hurricane Carol on August 31 to a person's waist, with waves rolling even higher. The fact that the maximum intensity of the storm coincided with the time of high water combined to wreak more damage than otherwise. Another foot in the rise would have permitted the camel to ride over the top of the fender piles, causing more extensive damage to the pier. However, the platform of the pier was lifted off its foundation, and then on the recession of the waters was left resting insecurely on a washout in the wall foundation.

Seawater to a depth of a foot or more entered the basement of the laboratory building causing damage to equipment and fixtures. One window was blown out, and the corner of the building used as a carpenter shop was slightly undermined.

The Institution-owned property, across the street from our main building was badly flooded with salt water which on the main street attained a height of two feet. The electric wiring in the buildings was condemned by the Falmouth building inspector, and this, considered with the dilapidated condition of one of the buildings previously rented as an apartment, was sufficient grounds for vacating it for this purpose. This building is now used as a storage of Institution equipment. The other building on the lot, a bungalow, has been renovated and continues as rental property.

The land on Nonamessett Island, across Woods Hole Great Harbor, which we lease for the storage of explosives, suffered from the inflow of the sea during Hurricane Carol. The several small buildings used as magazines were skewed on their foundations, and the small pier over which the explosives were landed and loaded was entirely swept away. This latter represents a sizeable restoration cost as does the repair on our main pier at Woods Hole.

A more detailed report of the hurricane damage is filed in the Institution's records along with the report of the hurricane of the year 1938.

The village property of the Institution consisting of Challenger House, Meteor House, Fram Cottage, l'Hirondelle, and the Barn (now renovated into three summer apartments and bachelors quarters) all are maintained in good condition. No major outlays have been necessary during the year. The Challenger Mess was operated throughout the summer but the patronage continued to dwindle which raises the question as to whether it should not be suspended until more use is indicated.

June 21 witnessed the dedication of the Office of Naval Research's new Laboratory of Oceanography, and following the acceptance by the Chief of Naval Research, delivery of the keys was made to this Institution for operation.

The legislation that provided for the Laboratory of Oceanography stipulated that it should be operated for the Navy by private interests. Accordingly, a contract called a facilities agreement has been executed between the Office of Naval Research and the Institution, providing for the use of the facilities for government contract research and for such other purposes as shall be approved. The running expenses are borne by the research contracts.

The benefits which are realized by the new laboratory is first the security which has been previously mentioned as a desirable attribute of the new arrangements. Further benefit lies in enabling the Institution to undertake new ventures in oceanographic research for which in recent years there has been little opportunity due to the excessively crowded condition and lack of laboratory space.

Personnel

The Research Staff in 1954 numbered 229.

As of July 1, 1954, the persons associated with the Institution were tabulated as follows:

RESEARCH STAFF	*1953*		*1954*	
Full time:				
Scientists and Technicians:				
At Woods Hole	79		94	
Off Campus	29		21	
Secretaries and Clerks	8		7	
Part time:				
At Woods Hole	43		44	
Off Campus	17		37	
Fellowship Holders	10		20	
Visiting Investigators	4	190	6	229*
SUPPORTING PERSONNEL				
Administrative:				
Department Heads and Assistants	12		10	
Secretaries and Clerks	19		12	
General Maintenance and Service Personnel	59		63	
Crews of Vessels	51	141	47	132
Grand Total		331		361

* Includes 82 Staff Appointees

It will be noted from the above listing of Institution personnel that while the Research Staff recorded an increase of approximately 17 per cent as of July 1, 1954, no increase occurred in supporting personnel. In fact a small reduction was effected in the latter.

It is with pleasure that we record the following additions to the Research Staff:

Appointment from July 1, 1954 to September 1, 1957:

Dr. Vaughn T. Bowen	Geochemist

Appointments for a period of one year from September 1:

Earl W. Barrett	Research Associate in Meteorology
L. A. Earlston Doe	Associate in Physical Oceanography
Robert A. Lufburrow	Research Associate in Physics
Jerome Namias	Associate in Meteorology
David M. Owen	Research Associate in Underwater Photography
F. Claude Ronne	Research Associate in Photography
George T. Scott	Associate in Physiology
Allard T. Spencer	Research Associate in Engineering
Thomas T. Sugihara	Associate in Geochemistry
Gunther K. Wertheim	Associate in Physical Oceanography
Geoffrey G. Whitney, Jr.	Research Associate in Physical Oceanography

Appointments for the period from December 16, 1954 to August 31, 1955:

John G. Bruce, Jr.	Research Associate in Physics
Herbert Small	Research Associate in Electronics
Ralph F. Vaccaro	Research Associate in Microbiology

Reappointments of Staff Members, whose terms expired in September, were made in all cases with the exception of Dr. William S. Butcher whose new appointment, that of Associate in Geology is due to his resignation as a full-time member which was accepted last year. Other appointment changes were effected in the cases of both Dr. Bostwick H. Ketchum and Dr. Alfred C. Redfield, namely from Senior Biologist to Senior Oceanographer respectively.

It is with regret that we accepted the resignations of Dr. Frank T. Dietz, Dr. George W. Wheeler and Mr. Kenneth G. McCasland.

The Institution lost through death, the services of Mr. Nathaniel R. Wing, Janitor, who passed away September 24, 1954 after more than twelve years of faithful and efficient service.

Several of the Staff visited Europe during the year either to attend international scientific meetings or to remain for more prolonged study. The list includes Dr. Edward H. Smith, the Director, who as the Reporter for Oceanography on the U. S. National Committee for the International

Geophysical Year attended the Special Committee's meetings at Rome, September 28–October 4. Following their adjournment, Dr. Smith visited for a day or less, oceanographic laboratories at Hamburg, Germany, Bergen, Norway, and Wormley, England. Visits were also made to the Meteorological Institute at Stockholm and the Department of Meteorology at Imperial College, London.

Mr. William S. von Arx attended the meetings of the International Union of Geodesy and Geophysics in Rome in September. He took part in the symposium on Current Measurements of the Association Internationale d'Océanographie Physique. Mr. von Arx also visited the Laboratoire National d'Hydraulique in Chaton, France, and gave a seminar on rotating models of the ocean circulation. In England, he visited Cambridge University, the Imperial College of Science and Technology and the newly established National Institute of Oceanography at Wormley. Mr. von Arx participated in the series of opening lectures at the Institute of Meteorology of the University of Stockholm.

Mr. Harry J. Turner attended the symposium on oyster and mussel culture of The International Council for the Exploration of the Sea at Paris, in October. Included in Mr. Turner's trip were visits to the Marine Zoological Station at Den Helder and the Government Fisheries Laboratory, Bergen-op-Zoom, Holland. He also visited several marine stations in Denmark, Sweden, and England.

Dr. Mary Sears attended meetings of the Joint Commission on Oceanography and the Union Géodesique et Géophysique Internationale at Rome, Italy in September. She then visited the Musée Océanographique in Monaco, the Zoologisch Museum in Amsterdam, the British Museum, and laboratories in Copenhagen, Oslo and Southampton.

In September, Dr. Willem V. R. Malkus left for England to continue his research program in connection with accelerated oceanographic studies and instrumentation. He will conduct his research at the National Institute of Oceanography, Wormley, near Godalming, Surrey, England. During his stay abroad, Dr. Malkus will visit other oceanographic laboratories.

Dr. Joanne Malkus went on leave of absence from the Institution in September to continue her research program in cloud physics at the Imperial College, London, for a period of approximately one year. This program in London is supported by a fellowship from the Munitalp Foundation. Dr. Malkus is also a holder of a fellowship from the John Simon Guggenheim Foundation.

Dr. Jule G. Charney, Professor of Meteorology at the Institute of Advanced Study, Princeton, New Jersey, was the Woods Hole Oceanographic Associates' Lecturer for 1954. Dr. Charney gave a series of six lectures on "Scale and Stability in Planetary Fluid Motions."

The following were awarded honoraria, grants, or fellowships during the year:

Bermuda Biological Station for Research
Bowen, E. G.
Charney, Jules G.
Doe, L. A. Earlston
Faller, Alan J.
Gabriel, Vittali G.
Guillard, Robert R. L.
Hazen, William E.
Leahy, Richard G.
Miller, Richard S.
Moore, James R. III
Montgomery, Raymond B.
Moulton, James M.
Nicholson, John R.
Nielsen, E. Steemann
Pierce, E. Lowe
Plunkett, Mary A.
Raymont, John E. G.
Riley, Gordon A.

It is desired to record in this section the action of the Members of the Corporation at their annual meeting at Woods Hole, August 12 in re-electing for another four-year period the following trustees whose terms expired in 1954:

Horace S. Ford
Albert E. Parr
Arnaud C. Marts
Athelstan F. Spilhaus
Selman A. Waksman

In addition Charles Francis Adams, Jr., was elected to fill the vacancy on the Board occasioned by the death of his father.

It is with deep regret that the passing of Mr. Charles Francis Adams is recorded. He was one of our earliest trustees whose prudent advice and sound financial counsel measurably added to the stature of the Institution. The Chairman of the Board has contributed a moving tribute in the record to Mr. Adams,—a lifelong friend of loyal and upright character.

At the Trustee's annual meeting on August 12 the following persons were elected as Members of the Corporation:

Charles F. Adams, Jr.
Ferdinand Eberstadt
Robert E. McConnell
Frank Pace, Jr.
John A. Gifford
Noel B. McLean

The persons whose names are listed below were members of the Institution (additional to those otherwise listed) for a period of six months or more during the calendar year 1954.

RESEARCH ASSISTANTS, ENGINEERS, AND TECHNICIANS

Andersen, Nellie E.
Athearn, William D.
Atwood, Barbara A.
Baldwin, Elizabeth E.
Barstow, Elmer M.
Bennett, Paul E.
Bergstrom, Stanley W.
Berry, Audrey W.
Black, William A.
Bonini, William E.
Bradshaw, Alvin L.
Cain, Henry A.
Campbell, Sybil A.
Cangiamila, Angelo
Carlson, Edgar
Carter, Alwyn L.
Chase, James F.
Chute, Edward H.
Chute, Nancy W.
Conover, John T.
Corwin, Nathaniel
Creitz, Grace I.
Davis, Lee C.
Davis, Priscilla K.
Day, C. Godfrey
Dingwell, Paul E.
Duys, Gerritt, Jr.
Edwards, Melville E.
Edwards, Richard S.
Faller, Alan J.

RESEARCH ASSISTANTS, ENGINEERS, AND TECHNICIANS (Continued)

Fee, Frances M.
Foster, Donald B.
Fraser, John G.
Hayes, Carlyle R.
Hoadley, Lloyd D.
Hodgson, Sloat F.
Kahler, Yolande A.
McCasland, Kenneth
Moss, William M.
Pasley, Gale G., Jr.
Pierce, Phebe
Pingree, Frederick deW.
Poole, Stanley E.
Purinton, Charles S.
Raiche, Shirley A.
Rose, John C.
Rutstein, Milton S.
Schroeder, Elizabeth H.
Shearer, Barbara J.
Shultz, William S.
Soderland, Eloise M.
Thayer, Lawrence A.
Thayer, Mary C.
Torphy, Shannon R.
Volkmann, Gordon H.
Volkmann, Suzanne B.
Walsh, Martha A.
Wilkins, Charles H.
Wilkins, Evangeline T.
Witzell, Warren E.

TECHNICAL CLERKS AND SECRETARIES

Allen, Ethel B.
Beehan, Elizabeth M.
Bergstrom, Eileen S.
Bradley, Mabel D.
Brailey, Leola R.
Dow, Evelyn
English, Jean
Glaeser, Florence E.
Marshall, Sondra L.
Mellor, Florence K.
Ortolani, Mary
Ostiguy, Betty P.
Owen, Helen T.
Perry, Barbara L.
Phillips, Helen F.
Rogers, Dorothy
Scharff, Margaret
Smyth, Clara
Souza, Cecelia
Spooner, Joanne C.
Stewart, Doris H.
Thatcher, Beverly J.
Vest, Dolores E.
Vest, Dolores R.
Wilson, Esther N.

ADMINISTRATIVE AND SECRETARIAL PERSONNEL

Backus, Jeanne M.
Behrens, Henry G.
Broadbent, Madeline P.
Bryant, Edwin T.
Camper, Barbara B.
Casiles, Phyllis M.
Crocker, Marion W.
Donald, Mary
Douthart, Dorothy E. S.
Ferris, Alice H.
Ferris, George A.
Griffin, T. S. Perry
Hatzikon, Kaleroy L.
Sandblom, John D.
Young, Anita M.

TECHNICAL SERVICES PERSONNEL

Bailey, Frank A.
Blake, Forrest W.
Bodman, Ralph H.
Bowman, Warren O.
Brigham, Robert K.
Condon, J. William
Dimmock, Richard H.
Dunkle, William M., Jr.
Eldridge, Stanley N.
Fairchild, Richard G.
Feldman, Joel
Fisher, Stanley O.
Gallagher, Gloria S.
Gallagher, William F.
Gaskell, Fred
Gifford, James E.
Grant, Carlton
Hodgkins, Harry L.
Howland, Myron P., Jr.
Kaplet, Dorothy
Morrison, Kenneth
Nelson, Dona E.
Penniman, Norman
Perry, Allison E.
Perry, Leonard S.
Rennie, Thomas D.
Spooner, Charles E.
Stimpson, John W.
Weeks, Robert G.
Wing, Carleton R.
Wing, Nathaniel (deceased)

MAINTENANCE, HOUSING AND CUSTODIAL PERSONNEL

Backus, Harold
Christian, John A.
Fielden, Frederick E.
Salthouse, James
Solberg, Otto
Souza, Matthew R.
Sparks, Elizabeth C.
Stansfield, Richard
Tometich, Louis J.
Turner, Catherine
Wilde, Phillips B.
Woodward, Fred C., Jr.
York, Javan D.

OFFICERS AND CREWS OF VESSELS, BOATS, AND AIRCRAFT

Adams, Malcolm H.
Backus, Cyril
Bailey, James S.
Barros, George M.
Bisaillon, Ralph
Blute, John J.
Boyden, Deane G.
Bradley, John III
Bray, W. Scott
Cabral, John V.
Casiles, David F.
Cavanaugh, James J.
Clarkin, James J.
Colburn, Arthur D., Jr.
Cook, Hans
Copestick, Louis B.
Cornell, Thomas L.
Coughlin, Brooks W.
Day, Joseph V.
Fournier, Richard A.
Gingrass, Norman
Graffam, Robert
Harvey, Stanley A.
Hay, William, Jr.
Howe, Paul M.
Howland, Paul C.
Karlson, Arvid
Lambert, Joseph L.
Lyon, Thomas
Mackey, Malcolm R.
Matthews, Francis S.
McCann, Clement L., Jr.
Moffet, Ivan L.
Mysona, Eugene J.
Nailor, David A.
O'Brien, Warren E., Jr.
Palmer, William E.
Roderick, Milton
Rose, Lawrence
Seibert, Harry H.
Shields, William J.
Smith, John J.
Speight, Carl W.
Sutherland, Peter A.
Van Looy, Felix J.
Wagner, Richard M.
Wilde, Donald F.

A new system of retirement benefits for the personnel was established during the year in place of the plan which had been in effect practically ever since the Institution was founded but had in recent years fallen into disuse. The plan as adopted by the Board, and put into effect as of July 1, 1954, offers a greater financial security to those permanently working at the Institution, and over the years it is anticipated that it will yield desirable profits in the form of soundly established internal relations and productive research.

The new retirement plan also has brought about a policy regarding the normal retirement age of Institution personnel which has been established as 65 years. In cases, however, of those individuals whose services are exceptionally valuable to the Institution, provision is made for their continuance on a year to year basis when so recommended by the Director and approved by proper authority.

Seven of our older employees not eligible under the new retirement plan on account of age, and having more than ten years of continuous service, will be kept on as long as practicable and their retirement worked out on as fair a basis as possible.

Acknowledgements

It is desired to record the support which the research program has received from the U. S. Navy Department's Office of Naval Research, the U. S. Bureau of Ships, the Bureau of Aeronautics, the Bureau of Ordnance, and the U. S. Air Force. The Commonwealth of Massachusetts, Division of Marine Fisheries, continued its support by furthering the shell-fish investigations. The appreciation of the Institution is hereby expressed to the above Government departments and agencies.

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National Science Foundation
Rockefeller Foundation
Research Corporation
Towns of Islip and Brookhaven
Munitalp Foundation
American Bureau of Shipping
Creole Petroleum Corporation

The gift of a sizeable lot of water front property by the General Foods Corporation together with a sum equal to the taxes for a period of one year, is gratefully recorded.

It is desired in this section to acknowledge with much appreciation the support which is growing stronger each year from the Woods Hole Oceanographic Associates. On February 26 the Associates held their annual dinner at the New York Yacht Club to some 150 members and guests following which Dr. Redfield spoke on the Institution's history and Captain Jaques-Yves Cousteau of the French Navy gave an illustrated lecture on his experiences in under-water diving by means of his invention, the aqua-lung. In April Mr. Noel B. McLean, President of the Edo Corporation, was elected Chairman of the corporate committee of the Associates. Earlier we have mentioned the Associates lectureship given in July. On August 7 the Associates held their annual cruise in Atlantis, when approximately 150 members and guests followed the start of the New York Yacht Club fleet race from Vineyard Haven to Nantucket. During the cruise, in perfect weather, oceanographic instruments were demonstrated and aqua-lung divers descended to the bottom of Vineyard Sound to bring up specimens.

"Oceanus," the modest little magazine which has been published at the Institution to keep the Associates currently informed on oceanographic events was stepped up to an issue of four times a year. At the end of the year the Associates numbered 124 individuals and 13 corporation members,—a growing organization of which we are justly proud.

During the year a positive force and policy was set in motion to add capital to the endowment fund of the Institution in the form of a brochure entitled, "Perpetuating Your Love for the Sea." Captain Marion Eppley accepted the Chairmanship of an Endowment Committee, by whose efforts and the distribution of the brochure, it is hoped through the years, that the capital endowment of the Institution will grow.

V. TREASURER'S REPORT

THE accounts for the year 1954 have been audited by Lybrand, Ross Bros. & Montgomery.

The book value of Endowment Funds at December 31, 1954 was $3,023,151, of which $603,731 represents the accumulated net gains from sales of investments, and $2,419,420 represents the original value of Endowment Funds. The market value of Endowment Assets on the same date was $4,246,844, including cash and advance to Current Funds. Schedule D shows an analysis by major groups of securities of the Endowment investments, and the income received therefrom.

The income received on Endowment assets, including interest charged on the advance to current funds was $149,255 for the year ended December 31, 1954, compared with $151,862 for the calendar year 1953. This income represents a return on the Endowment investments of 3.5% on the year-end market value, 4.9% on the book value, and 6.2% on the original value of the Endowment.

The Executive Committee, upon the recommendation of the Finance Committee, voted to allocate for 1954 Operating Expenses from the Endowment Income 5.3% of the original book value of the Endowment which amounted to $128,229. The balance of Endowment Income, $21,026, was transferred to the Income and Salary Stabilization Reserve. The rate was the same as voted in 1953.

On March 17, 1954 the General Foods Corporation made a generous gift to the Institution of its former marine base at New Street, East Boston. In addition to the property, they made a cash gift of $15,000 at the same time. These gifts were made without restriction. As the Institution, after careful consideration, feels it cannot use the property, it has been offered for sale. The value of the property is not included in the balance sheet, but the net proceeds will be added to Current Fund Assets when it is sold, for such disposition as may hereafter be determined.

The note payable to the New England Trust Company of $295,000 was paid off during the year, and replaced by an advance from the Endowment Funds to Current Funds. This advance was $175,000 on December 31, 1954. Interest on this advance at 2¼% is credited to Endowment income out of our Current Expenses in place of the interest formerly paid to the bank. The 2¼% rate is approximately the rate of interest received on the Government bonds sold to provide the cash for the advance. The net result of the above transaction was to save $5,132 in annual interest charges over the amount of interest paid in 1953.

Deferred Charges amounting to $71,033, as shown at the bottom of the balance sheet, represent expenditures for the benefit of future years. A proportionate part of these charges will be added to Current Costs, or other appropriate accounts, as the benefits accrue.

The details of Unexpended Balances of Gifts and Grants allocated to Research are shown in Schedule C, and the balance, representing contributions of the Woods Hole Oceanographic Associates as yet not specifically allocated, amounts to $35,957.

During the year contributions to the old Retirement Plan were ended by vote of the Trustees, and the new Woods Hole Oceanographic Institution Employees' Retirement Plan and Trust was voted and went into effect as of July 1st. The first contribution to this Trust, amounting to $26,810, was made early in January, 1955, and appears on the balance sheet as a Current Liability as of December 31, 1954. The amount was charged to Indirect Costs and a large proportion was recovered through the operation of the Overhead Recovery provisions in our Governmental contracts. The balance remaining in the old Retirement Fund, which is in the custody of the Treasurer as Trustee, amounted to $59,307 as at December 31, 1954. This amount represents balances held in separate savings bank accounts for ten individuals. We will continue to hold these amounts in this way until they become payable to the participants or their estates under the provisions of the original Retirement Plan.

At the suggestion of the new auditors, the Treasurer's Report and financial statements are being presented in a different form than in the past. The Income Statement this year includes all income of the Institution. In prior years Receipts under Contracts have not been included. Schedules A and B show details of Direct Costs of Research Activity, General and Administration Expenses, and Expenses of Plant Operation. It is interesting to note that for each dollar received, 74 cents were spent for Direct Costs of Research Activity, 19 cents for General and Administration Expenses and 7 cents for Plant Operation and Miscellaneous.

BALANCE SHEET

As at December 31, 1954

ASSETS

Endowment Fund Assets:		
Investment securities (Schedule D):		
Bonds (market quotations $1,635,198)		$1,611,987
Stocks (market quotations $2,415,052)		1,214,570
		$2,826,557
Cash		21,594
Advance to current funds		175,000
		$3,023,151
Plant Assets (note A):		
Laboratory plant and equipment		$ 512,152
Vessels and equipment		364,983
Other property		161,541
		$1,038,676
Current Fund Assets:		
Cash		$ 72,626
Accounts receivable:		
U. S. Government	$ 52,368	
Other	5,120	57,488
Unbilled costs on research contracts:		
U. S. Government	$283,461	
Other	7,302	290,763
Supply inventories		25,287
Deferred charges (note B)		71,033
		$ 517,197
		$4,579,024

LIABILITIES

Endowment Funds:		
Unrestricted		$2,000,000
For upkeep of plant		419,420
Accumulated net gain on sale of investments		603,731
		$3,023,151
Funds Invested in Plant		$1,038,676
Current Liabilities and Funds:		
Accounts payable and accrued expenses		$ 40,632
Contribution payable to employees' retirement plan and trust		26,810
Advance from endowment funds		175,000
Unexpended balances of gifts and grants:		
For research (Schedule C)		30,866
Oceanographic Associates		35,957
General fund:		
General plant and equipment reserve	$150,024	
Income and salary stabilization reserve	44,659	
Unappropriated	13,249	207,932
		517,197
		$4,579,024

Notes: A — Since 1945 the Institution has provided for depreciation of plant assets other than vessels at annual rates of 2% on buildings and 5% to 25% on equipment, carrying the amounts to general plant and equipment reserve.

B — Real estate received as a gift in 1954 and held for sale at December 31, 1954 is not included in assets; it will be added to current fund assets when sold at the net amount of the proceeds from sale. Deferred charges include $9,400 net expenses in connection with this property.

STATEMENT OF INCOME, OPERATING EXPENSES AND UNAPPROPRIATED GENERAL FUND

For the Year Ended December 31, 1954

INCOME:		
Reimbursement of sponsored research activity:		
For direct costs		$1,288,026
For indirect costs		429,069
		1,717,095
Endowment income after amortization of bond premiums (Schedule D)	$149,255	
Less amount added to income and salary stabilization reserve	21,026	128,229
Miscellaneous		1,405
Total income availed of		1,846,729
OPERATING EXPENSES:		
Direct costs of research activity (Schedule A):		
Salaries and wages		696,227
Vessel operations		382,360
Materials and services		225,275
Travel		68,687
		1,372,549
Indirect costs:		
General and administration (Schedule B)	350,857	
Plant operation (Schedule B)	116,622	
Miscellaneous (including $4,000 reserved for replacement of equipment)	11,432	478,911
Total operating expenses		1,851,460
EXCESS OF OPERATING EXPENSES		4,731
UNAPPROPRIATED GENERAL FUND, JANUARY 1, 1954		17,980
UNAPPROPRIATED GENERAL FUND, DECEMBER 31, 1954		$ 13,249

SCHEDULE A

DIRECT COSTS OF RESEARCH ACTIVITY

For the Year Ended December 31, 1954

	Salaries and Wages	Vessel Operations	Materials and Services	Travel	Total
U.S. GOVERNMENT CONTRACTS	$596,127	$367,104	$213,584	$59,062	$1,235,877
OTHER SPONSORED RESEARCH	39,636	1,782	5,561	5,170	52,149
Total direct costs of sponsored research	635,763	368,886	219,145	64,232	1,288,026
INSTITUTION RESEARCH	60,464	13,474	6,130	4,455	84,523
Total direct costs of research	$696,227	$382,360	$225,275	$68,687	$1,372,549

SCHEDULE B

GENERAL AND ADMINISTRATION EXPENSES AND EXPENSES FOR PLANT OPERATION

For the Year Ended December 31, 1954

GENERAL AND ADMINISTRATION

GENERAL EXPENSES:		
Staff benefits:		
Contributions to retirement plan effective July 1, 1954 and to retirement fund discontinued at that date		$27,969
Social security taxes		17,048
		45,017
Grants and fellowships		18,893
Purchase of books and equipment		26,674
Shop services		55,233
Housing and mess, net		6,331
Publications		8,893
ADMINISTRATION EXPENSES:		
Salaries and wages	$137,968	
Insurance, travel, supplies and other	59,507	197,475
		358,516
Less equipment charged to general plant and equipment reserve		7,659
		$350,857

PLANT OPERATION

SALARIES AND WAGES		$47,820
PROVISION FOR DEPRECIATION (credited to general plant and equipment reserve)		23,516
OTHER REPAIR COSTS	$20,311	
HEAT, LIGHT AND POWER	15,494	
OTHER	9,481	45,286
		$116,622

SCHEDULE C

SUMMARY OF GIFTS AND RECEIPTS FOR RESEARCH

Year Ended December 31, 1954

	Unexpended Balance January 1, 1954	Received	Expended		Other Charges or (Credits)	Unexpended Balance December 31, 1954
			Direct Costs	Indirect Costs		
American Society of Limnology and Oceanography		$915	$769	$146		
Arctic Institute	$635	1,407	1,498	544		
Barataria Bay Model	455		325			$130
Blue Dolphin		313	211	102		
Boat Lemming		342	342			
Columbia University			(34)		$34[1]	
Commonwealth of Massachusetts	4,795	20,000	10,696	4,988		9,111
Creole Petroleum Corporation		5,349	4,221	1,128		
Great South Bay Project		2,000	2,358	1,353	(1,711)[1]	
Manufacture, sale and calibration of instruments			1,972	2,991	(4,963)[2]	
Munitalp Foundation		10,000			4,200[3]	5,800
National Science Foundation:						
Biological productivity		2,760	2,400	360		
Buoyancy control in fish		5,373	4,818	555		
Penetration of light		6,200	4,450	667		1,083
Properties of chlorophyll		4,700	1,925	289		2,486
Oceanographic Associates		5,000	584	58		4,358
Research Corporation	438		339	63	(1,370)[2]	1,406
Rockefeller Foundation:						
Marine physiology	19,686	12,000	12,625		13,611[4]	5,450
Meteorological research		2,500	1,458			1,042
Underwater swimming manual		2	1	1		
U.S. Coast Guard Oceanographic Unit		1,676	1,191	306	179[1]	
	$26,009	$80,537	$52,149	$13,551	$9,980	$30,866

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[1] Credited or (charged) to Institution operating expenses.

[2] Receipts from sales or services.

[3] Payments to designated award recipients.

[4] Returned to donor.

Schedule D

SUMMARY OF INVESTMENTS

As at December 31, 1954

	Book Amount	% of Total	Market Quotation	% of Total	Income
Bonds:					
U.S. Government	$527,518	18.66	$525,230	12.97	$11,723
Railroad	419,371	14.84	437,206	10.79	10,392
Public utility	228,582	8.09	228,657	5.65	3,769
Industrial	231,468	8.19	238,705	5.89	4,037
Financial and investment	205,048	7.25	205,400	5.07	(780)
Total bonds	$1,611,987	57.03	$1,635,198	40.37	$29,141
Stocks:					
Preferred	$368,023	13.02	$405,313	10.01	$19,936
Common:					
Public utility	$275,412	9.74	$410,901	10.15	$22,435
Industrial	429,976	15.22	1,310,430	32.35	61,344
Miscellaneous	141,159	4.99	288,408	7.12	12,208
Total common stocks	$846,547	29.95	$2,009,739	49.62	$95,987
Total stocks	$1,214,570	42.97	$2,415,052	59.63	$115,923
Total Investments	$2,826,557	100.00	$4,050,250	100.00	$145,064

Interest on Advance to Current Funds Charged to Miscellaneous Operating Expense 4,191

Total Endowment Fund Income $149,255

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

We have examined the balance sheet of Woods Hole Oceanographic Institution as at December 31, 1954 and the related statement of income, operating expenses and unappropriated general fund for the year then ended. Our examination was made in accordance with generally accepted auditing standards, and accordingly included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances.

In our opinion, the accompanying financial statements present fairly the position of Woods Hole Oceanographic Institution at December 31, 1954 and the results of its operations for the year then ended.

Lybrand, Ross Bros. & Montgomery

Boston, Massachusetts
May 16, 1955

APPENDIX

ATLANTIS

Cruise No.	Depart	Arrive	From	To	Days	Chief Scientist—Remarks
196	18 Jan.	1 Feb.	Woods Hole	Miami	15	H. Johnson
	6 Feb.	19 Feb.	Miami	St. Thomas	14	H. Johnson
	22 Feb.	27 Feb.	St. Thomas	San Juan	6	H. Johnson
	1 Mar.	5 Mar.	San Juan	San Juan	5	H. Johnson
	8 Mar.	9 Mar.	San Juan	San Juan	2	H. Johnson
	15 Mar.	23 Mar.	San Juan	Nassau	9	H. Johnson
	24 Mar.	2 Apr.	Nassau	Woods Hole	10	H. Johnson
	7 Apr.	7 Apr.	Woods Hole	Boston	1	To Boston for annual
	19 May	19 May	Boston	Woods Hole	1	drydocking
197	24 May	28 May	Woods Hole	Woods Hole	5	H. Johnson
198	7 June	17 June	Woods Hole	Woods Hole	11	W. Malkus
199	24 June	30 June	Woods Hole	Woods Hole	7	W. Schroeder
200	6 July	9 July	Woods Hole	Woods Hole	4	D. Frantz
201	14 July	17 July	Woods Hole	Woods Hole	4	H. Johnson
202	21 July	24 July	Woods Hole	Woods Hole	4	H. Johnson
203	26 July	5 Aug.	Woods Hole	Woods Hole	11	H. Stetson
204	7 Aug.	7 Aug.	Woods Hole	Woods Hole	1	Associates Cruise
205	9 Aug.	21 Aug.	Woods Hole	Woods Hole	13	H. Johnson
206	26 Aug.	30 Aug.	Woods Hole	Bermuda	5	J. Zeigler
	4 Sept.	10 Sept.	Bermuda	Woods Hole	7	J. Zeigler
207	10 Sept.	10 Sept.	Woods Hole	Boston	1	Hurricane precaution
	12 Sept.	12 Sept.	Boston	Woods Hole	1	
208	17 Sept.	26 Sept.	Woods Hole	Bermuda	10	L. Worthington
	28 Sept.	1 Oct.	Bermuda	Woods Hole	4	L. Worthington
209	10 Oct.	14 Oct.	Woods Hole	Woods Hole	5	H. Johnson
210	15 Oct.	15 Oct.	Woods Hole	Boston	1	Hurricane precaution
	16 Oct.	16 Oct.	Boston	Woods Hole	1	
211	17 Oct.	27 Oct.	Woods Hole	Woods Hole	11	R. Walden
212	3 Nov.	8 Nov.	Woods Hole	Bermuda	6	L. Worthington
	9 Nov.	26 Nov.	Bermuda	Barbados	18	L. Worthington
	30 Nov.	30 Nov.	Barbados	Barbados	1	L. Worthington
	1 Dec.	1 Dec.	Barbados	Barbados	1	L. Worthington
	2 Dec.	2 Dec.	Barbados	Barbados	1	L. Worthington
	3 Dec.	19 Dec.	Barbados	Woods Hole	17	L. Worthington
		Total			213	

CARYN

Cruise No.	Depart	Arrive	From	To	Days	Chief Scientist—Remarks
71	17 May	21 May	Woods Hole	Woods Hole	5	J. Zeigler
72	28 May	1 June	Woods Hole	Bermuda	5	L. Worthington
	2 June	13 June	Bermuda	St. Thomas	12	L. Worthington
	17 June	24 June	St. Thomas	Bermuda	8	L. Worthington
	25 June	29 June	Bermuda	Woods Hole	5	L. Worthington
73	12 July	19 July	Woods Hole	Woods Hole	8	J. Zeigler
74	20 July	21 July	Woods Hole	Woods Hole	2	R. Edwards
75	22 July	24 July	Woods Hole	Woods Hole	3	D. Frantz
76	25 July	29 July	Woods Hole	Woods Hole	5	R. Edwards
77	3 Aug.	5 Aug.	Woods Hole	Woods Hole	3	G. Clarke
78	5 Aug.	15 Aug.	Woods Hole	Woods Hole	11	H. Johnson
79	19 Aug.	29 Aug.	Woods Hole	Woods Hole	11	F. Fuglister
80	2 Sept.	4 Sept.	Woods Hole	Woods Hole	3	D. Frantz
81	9 Sept.	9 Sept.	Woods Hole	Boston	1	Hurricane precaution
	12 Sept.	12 Sept.	Boston	Woods Hole	1	
82	15 Sept.	17 Sept.	Woods Hole	Woods Hole	3	D. Owen
83	15 Oct.	15 Oct.	Woods Hole	Boston	1	Hurricane precaution
	17 Oct.	17 Oct.	Boston	Woods Hole	1	
84	19 Oct.	22 Oct.	Woods Hole	Woods Hole	4	W. Moss
85	28 Oct.	2 Nov.	Woods Hole	Woods Hole	6	W. Athearn
86	30 Nov.	2 Dec.	Woods Hole	Woods Hole	4	R. Walden
87	9 Dec.	9 Dec.	Woods Hole	Woods Hole	1	R. Walden
88	17 Dec.	17 Dec.	Woods Hole	Boston	1	To Boston for annual
	30 Dec.	30 Dec.	Boston	Woods Hole	1	dry-docking
		Total			105	

BEAR

Cruise No.	Depart	Arrive	From	To	Days	Chief Scientist—Remarks
89	18 Jan.	23 Jan.	Woods Hole	Morehead City	6	F. Dietz
	26 Jan.	1 Feb.	Morehead City	Miami	7	F. Dietz
	7 Feb.	18 Feb.	Miami	St. Thomas	12	G. Wheeler
	23 Feb.	23 Feb.	St. Thomas	San Juan	1	G. Wheeler
	1 Mar.	5 Mar.	San Juan	San Juan	5	G. Wheeler
	11 Mar.	12 Mar.	San Juan	San Juan	2	G. Wheeler
	15 Mar.	23 Mar.	San Juan	Nassau	9	G. Wheeler
	24 Mar.	2 Apr.	Nassau	Woods Hole	10	G. Wheeler
90	18 May	18 May	Woods Hole	Woods Hole	1	A. Vine
91	19 May	19 May	Woods Hole	Woods Hole	1	A. Vine
92	25 May	28 May	Woods Hole	Woods Hole	4	J. Zeigler
93	1 June	6 June	Woods Hole	Woods Hole	6	W. Shultz
94	14 June	17 June	Woods Hole	Woods Hole	4	R. Edwards
95	25 June	25 June	Woods Hole	Woods Hole	1	R. Edwards
96	6 July	9 July	Woods Hole	Woods Hole	4	W. Athearn
97	14 July	14 July	Woods Hole	Woods Hole	1	W. Dow
98	21 July	24 July	Woods Hole	Woods Hole	4	J. Hersey
99	28 July	29 July	Woods Hole	Oyster Bay	2	Installation of equipment at Sperry Gyro Co.
	30 July	30 July	Oyster Bay	Woods Hole	1	
100	9 Aug.	20 Aug.	Woods Hole	Woods Hole	12	J. Hersey
101	24 Aug.	24 Aug.	Woods Hole	Woods Hole	1	C. Officer
102	25 Aug.	25 Aug.	Woods Hole	Woods Hole	1	C. Officer
103	27 Aug.	27 Aug.	Woods Hole	Woods Hole	1	G. Duys
104	9 Sept.	9 Sept.	Woods Hole	Woods Hole	1	C. Officer
105	10 Sept.	10 Sept.	Woods Hole	Boston	1	Hurricane precaution
	12 Sept.	12 Sept.	Boston	Woods Hole	1	
106	13 Sept.	17 Sept.	Woods Hole	Woods Hole	5	R. Backus
107	22 Sept.	22 Sept.	Woods Hole	Woods Hole	1	C. Officer
108	10 Sept.	14 Sept.	Woods Hole	Oyster Bay	5	J. Hersey
	15 Sept.	17 Sept.	Oyster Bay	Woods Hole	3	
109	3 Nov.	4 Nov.	Woods Hole	Woods Hole	2	H. Johnson
110	7 Nov.	9 Nov.	Woods Hole	Woods Hole	3	To Sperry Gyro Co. and return
111	10 Nov.	12 Nov.	Woods Hole	Woods Hole	3	H. Johnson
112	15 Nov.	15 Nov.	Woods Hole	Boston	1	To Boston for shipyard repairs
			Total		122	

PBY–6A

Flight No.	Date	Bases	Days	Chief Scientist—Remarks
	4 Jan.–5 Feb.	Local flights	11	
P-98	8 Feb.	Otis to Cherry Point		W. Richardson
	9 Feb.	Cherry Point to Miami, Fla.		
	10 Feb.	Miami to Charleston, S. C.		
	11 Feb.	Charleston to Otis	4	
	16 Feb.–23 Feb.	Local flights	4	
P-103	24 Feb.	Otis to Kindley, Bermuda		A. Bunker–W. Malkus
	26 Feb.	Kindley local		
	27 Feb.	Kindley local		
	28 Feb.	Kindley to Otis	4	
	4 Mar.–5 Mar.	Local flights	2	
	5 Mar.–29 Mar.	To Quonset for check and return	2	In for 720-hr check
P-108	31 Mar.	Otis to Argentia, Nfld.		W. Richardson
	6 Apr.	Argentia local		
	8 Apr.	Argentia local		
	9 Apr.	Argentia local		
	10 Apr.	Argentia local		
	11 Apr.	Argentia local		
	13 Apr.	Argentia local		
	14 Apr.	Argentia local		
	15 Apr.	Argentia local		
	17 Apr.	Argentia local		
	19 Apr.	Argentia local		
	20 Apr.	Argentia local		
	22 Apr.	Argentia to Otis	13	
	26 Apr.–29 Apr.	Local flights	2	
P-111	5 May	Otis to Cherry Point		A. Redfield
	6 May	Cherry Point to Daytona Beach		
	7 May	Daytona Beach to Cherry Point		
	8 May	Cherry Point to Atlantic City		
	9 May	Atlantic City to Otis	5	
	12 May–7 June	Local flights	10	
P-122	8 June	Otis to Elizabeth City		W. Richardson
	9 June	Elizabeth City to Otis	2	
	11 June–17 June	Local flights	3	
P-127	18 June	Otis to Quonset	1	Into check
P-128	2 July	Quonset to Otis	1	Out of check
	8 July–9 July	Local flights	2	
P-131	12 July	Otis to Kindley		W. Richardson
	14 July	Kindley local		
	15 July	Kindley local		
	16 July	Kindley to Otis	4	
	22 July–18 Nov.	Local flights	45	
P-176	21 Nov.	Otis to Elizabeth City		W. Richardson
	22 Nov.	Elizabeth City local		
	23 Nov.	Elizabeth City to Otis	3	
P-177	24 Nov.	Otis to Quonset	1	Maintenance
P-178	14–15 Dec.	Quonset to Pensacola, Fla.	1	Maintenance
	16–17 Dec.	Pensacola to Otis	1	Return flight
P-179	19 Dec.	Otis to Bermuda		W. Richardson
	21 Dec.	Bermuda to Otis	2	
	29 Dec.	Local flight	1	
		Total	124	

List of Contributions

LIST OF CONTRIBUTIONS

FROM THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

See Author Index in *Collected Reprints* 1950 for a complete list up to that year.

No. 366. Bostwick H. Ketchum. Plankton Algae and their Biological Significance. In: Manual of Phycology — an Introduction to the Algae and their Biology, Ch. 17, pp. 335–346. Gilbert M. Smith, Editor. Published by The Chronica Botanica Co., Waltham, Mass. 1951.

No. 401. W. S. Butcher. A New Species of *Nonion* (Foraminifera) from the Woods Hole Region. *Contr. Cushman Lab. Foram. Res.*, Vol. 24, (1), No. 308, pp. 21–23. 1948.

No. 402. Edward S. Deevey, Jr. On the Date of the Last Rise of Sea Level in Southern New England, with Remarks on the Grassy Island Site. *Amer. Jour. Sci.*, Vol. 246, pp. 329–352. 1948.

No. 403. Charles M. Weiss. The Abnormal Development of Tunicates Attached to Glass Surfaces Adjacent to Antifouling Paints. *Ecology*, Vol. 29, No. 2, pp. 215–218. 1948.

No. 404. Charles M. Weiss. The Seasonal Occurrence of Sedentary Marine Organisms in Biscayne Bay, Florida. *Ecology*, Vol. 29, No. 2, pp. 153–172. 1948.

No. 405. R. B. Montgomery. Vertical Eddy Flux of Heat in the Atmosphere. *Jour. Meteorology*, Vol. 5, No. 6, pp. 265–274. 1948.

No. 406. Hilary B. Moore. The Zooplankton of the Upper Waters of the Bermuda Area of the North Atlantic. *Sears Found., Jour. Mar. Res.*, Vol. 12, Art. 2, pp. 1–97. 1949. (Not included in *Collected Reprints*.)

No. 407. H. R. Seiwell. Evaluation of Sea-Surface Roughness from Underwater-Pressure Recordings. *Trans. Amer. Geophys. Union*, Vol. 29, No. 2, pp. 197–201. 1948.

No. 408. Henry Stommel. The Westward Intensification of Wind-Driven Ocean Currents. *Trans. Amer. Geophys. Union*, Vol. 29, No. 2, pp. 202–206. 1948.

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